NGLS DESIGN STUDY
AND
ACCELERATOR R&D

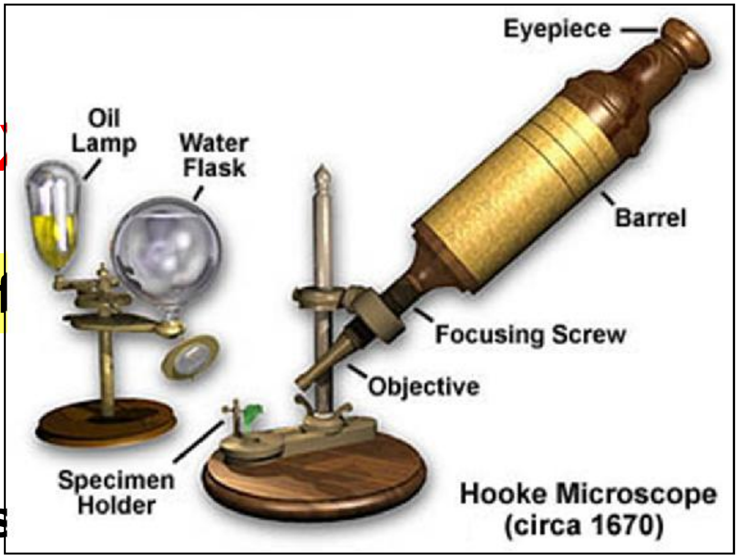
John Corlett for the NGLS Accelerator Systems Team

March 15, 2012

What is the NGLS?
Why do we need it – now?

NGLS will be the world's fastest X

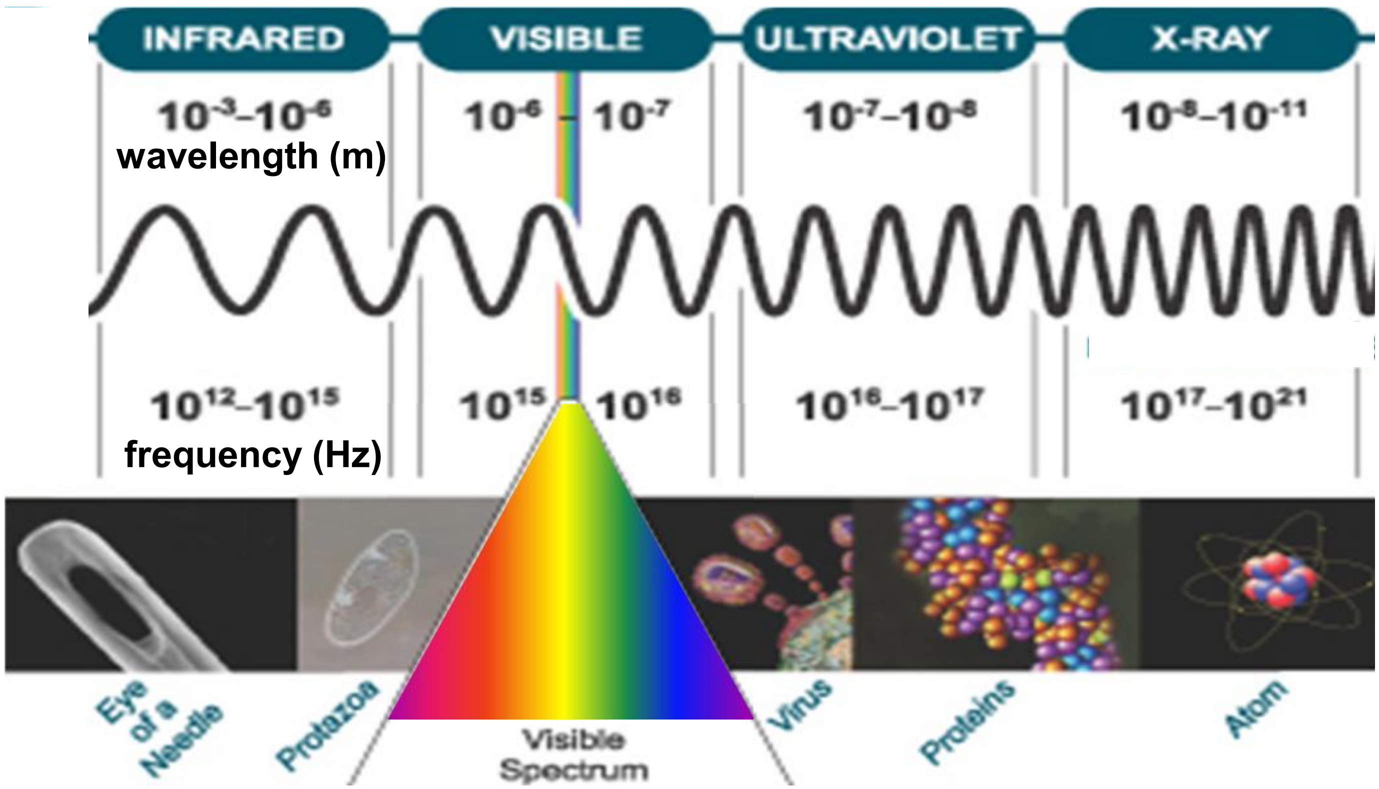
- High repetition rate X-ray laser with ultraf
- Significant impact on the DOE mission
    - Urgent energy science: photosynthesis

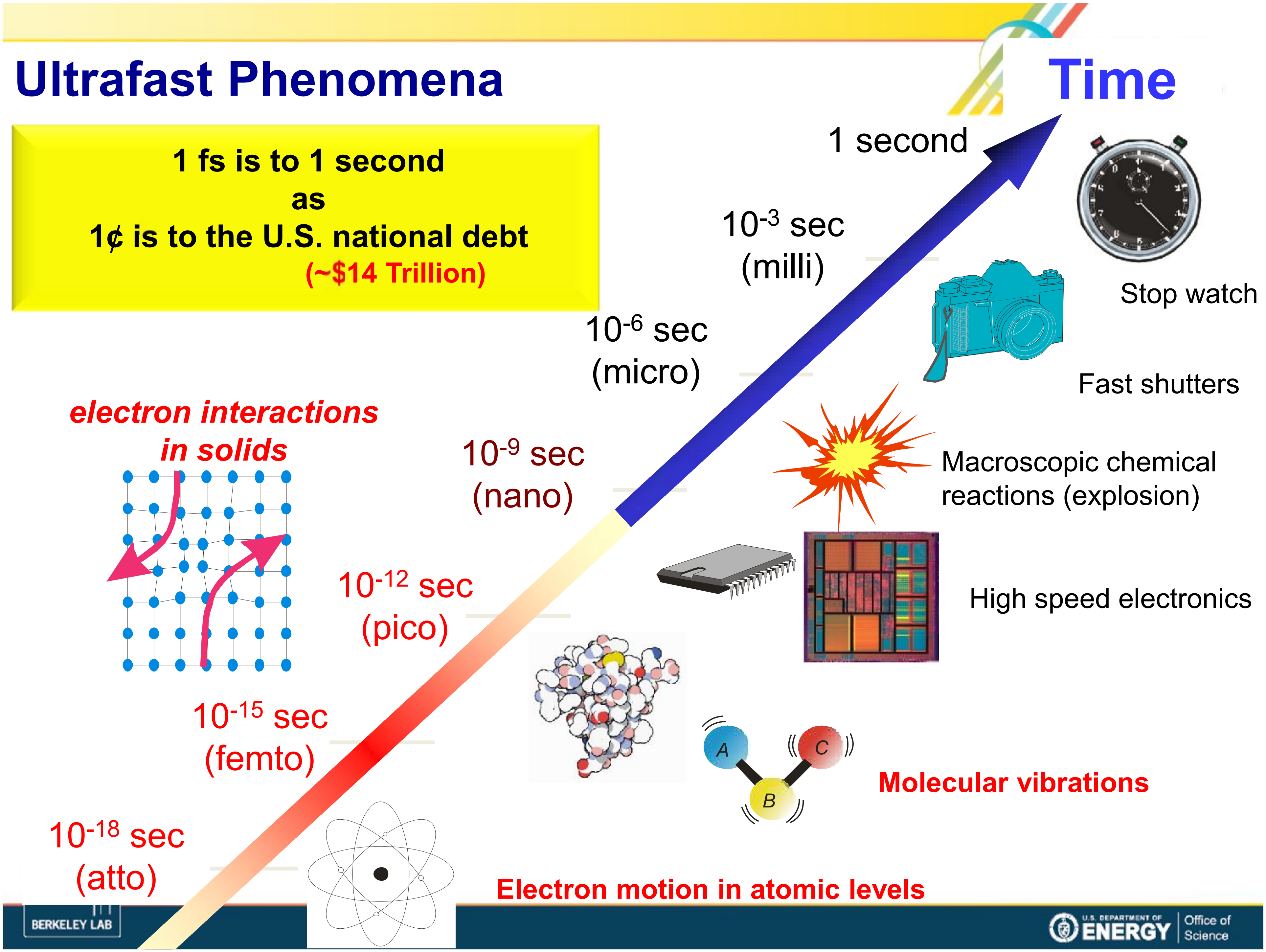


- Unique machine that will enable global leadership in critical areas
- Recent X-ray laser breakthroughs (LCLS/FLASH/FERMI@elettra) point the way…
    - Ten year time horizon, NGLS is not an incremental advance

Worldwide, no source – operating today or under construction – will be able to provide all the capabilities of NGLS

Light – Electromagnetic Spectrum

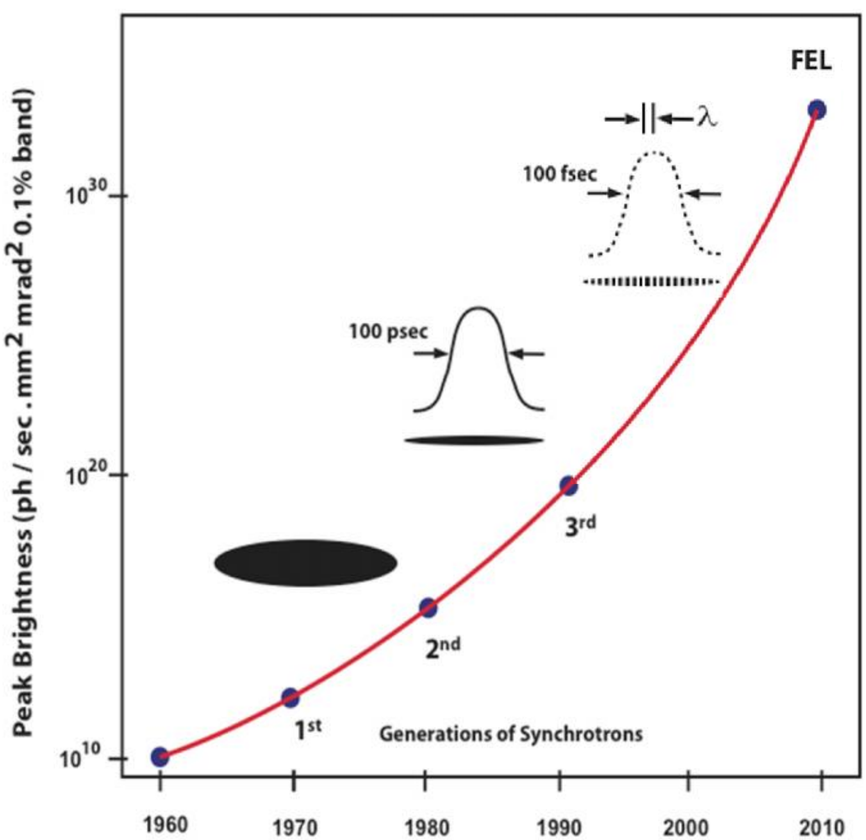


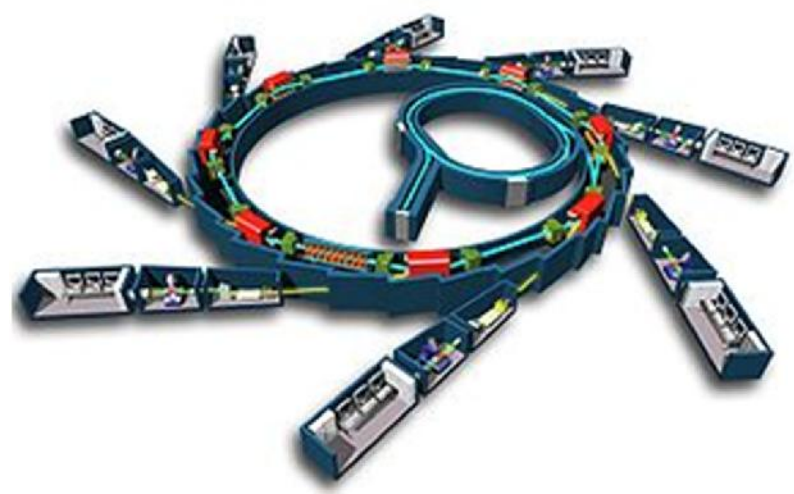


Ultrafast Phenomena
Time
1 fs is to 1 second
as
1¢ is to the U.S. national debt
(~$14 Trillion)
1 second
10^-3 sec
(milli)
10^-6 sec
(micro)
10^-9 sec
(nano)
10^-12 sec
(pico)
10^-15 sec
(femto)
10^-18 sec
(atto)
Stop watch
Fast shutters
Macroscopic chemical
reactions (explosion)
High speed electronics
electron interactions
in solids
A
B
C
Molecular vibrations
Electron motion in atomic levels
BERKELEY LAB
U.S. DEPARTMENT OF ENERGY
Office of Science

Three generations of light sources have driven X-ray science:

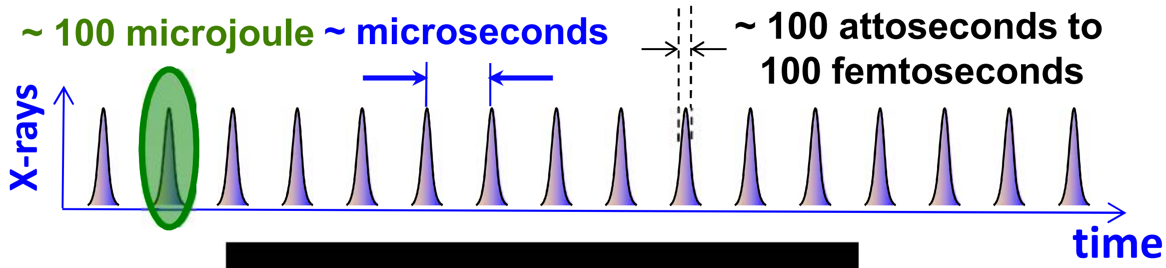
Next generation sources will be *intense, ultrafast, coherent*

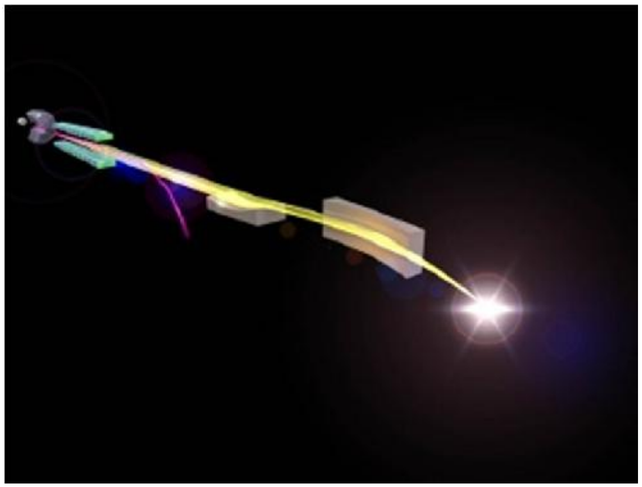


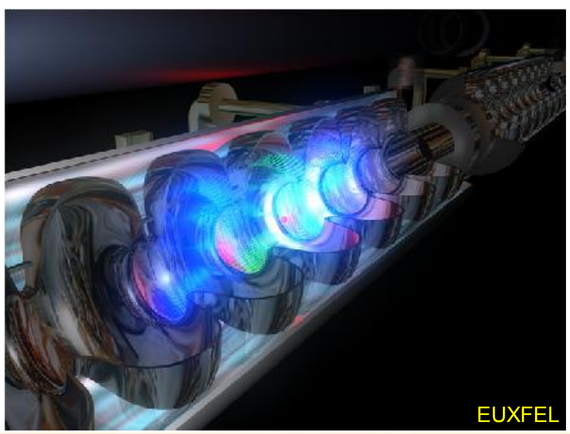


Synchrotron radiation from accelerated electron beams

What is the NGLS? – Technologies







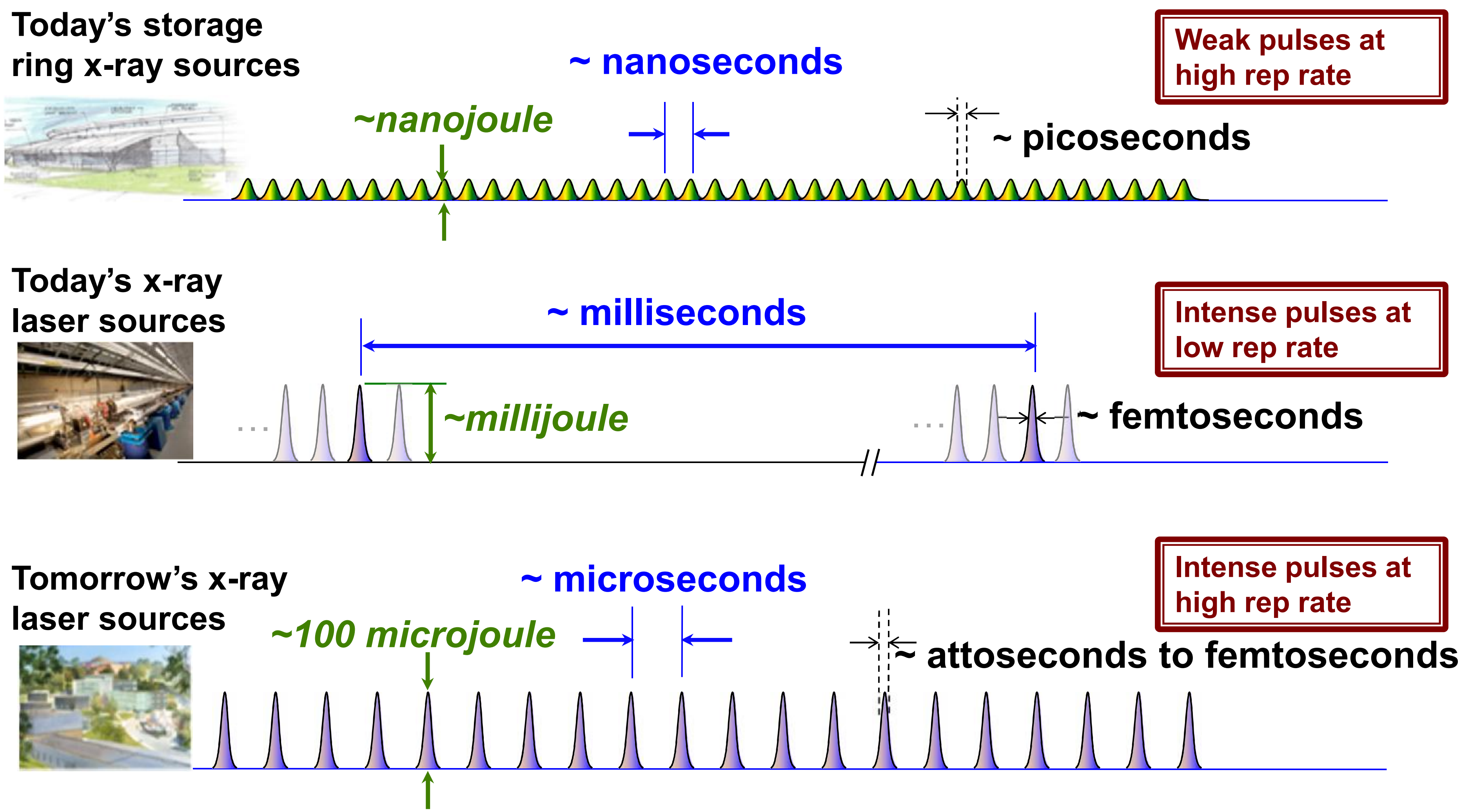
Goal: beams of intense, ultrafast, coherent X-ray pulses at high repetition-rate

Free electron lasers (FELs)provide intense, ultrafast, coherent, X-ray pulses

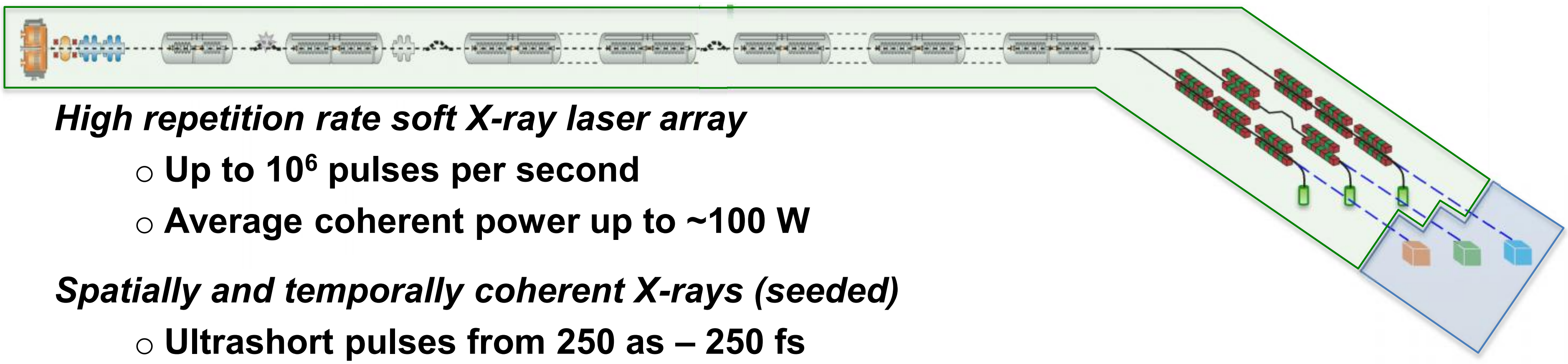
A superconducting accelerator and high rep-rate injector provides high brightness electron beam

Comparison with existing light sources

NGLS
next generation light source



NGLS Capabilities



High repetition rate soft X-ray laser array

- Up to 10^6 pulses per second
- Average coherent power up to ~100 W

Spatially and temporally coherent X-rays (seeded)

- Ultrashort pulses from 250 as – 250 fs
- Narrow energy bandwidth to 50 meV

Tunable X-rays

- Adjustable photon energy from 280 eV – 1.2 keV
  - higher energies in the 3rd and 5th harmonics
- Polarization control
- Moderate to high flux with 10^8 – 10^{12} photons/pulse

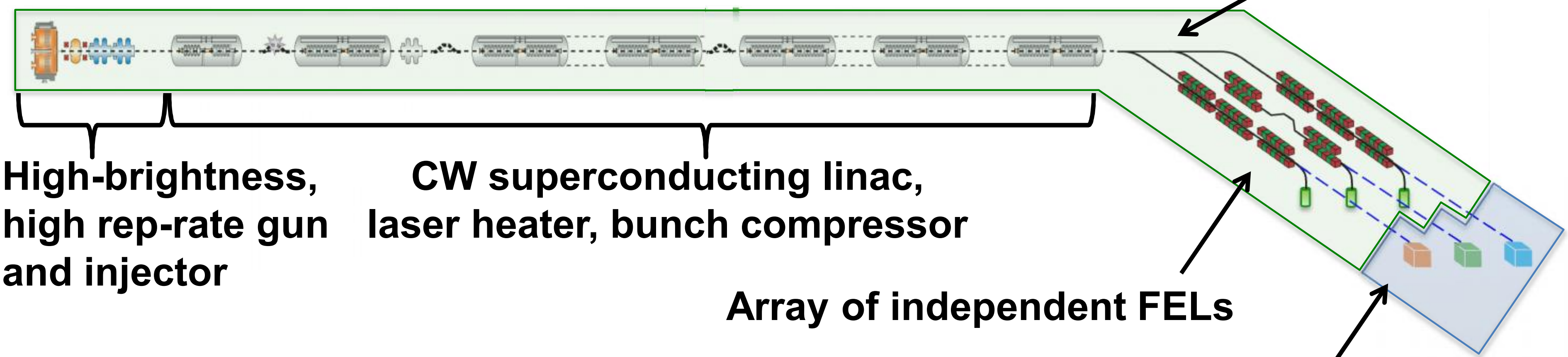
Expandable

- Capability
- Capacity

NGLS Approach

NGLS next generation light source

High average power electron beam distributed to an array of FELs from high rep-rate injector and CW SCRF linac



Beam spreader

High-brightness, high rep-rate gun and injector

CW superconducting linac, laser heater, bunch compressor

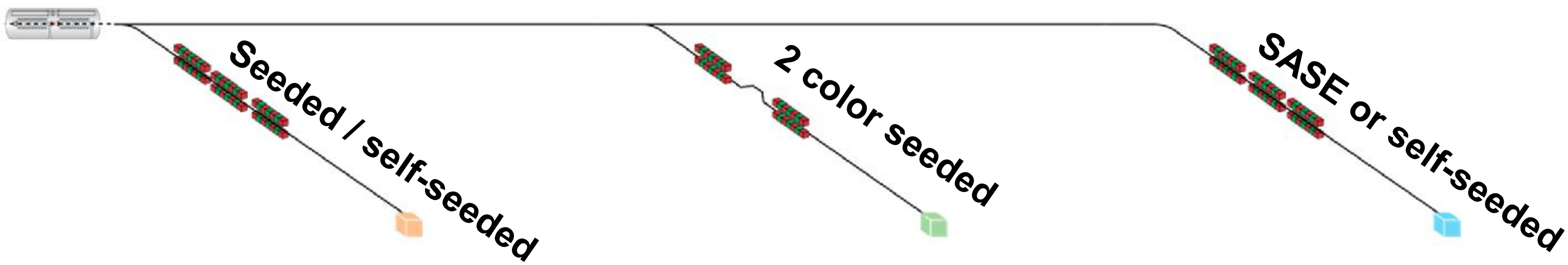
Array of independent FELs

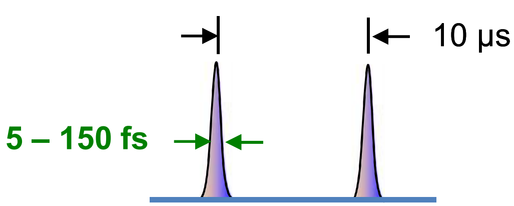
X-ray beamlines and endstations

NGLS offers significant advances over current capabilities:

- More photons per unit bandwidth
- More photons per second
- Shorter pulses
- Controlled trade-off between time and energy resolution

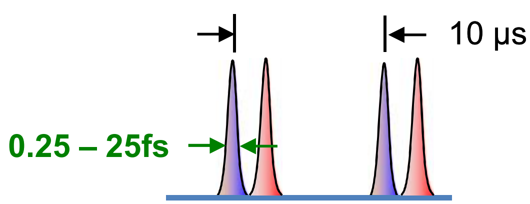
Three initial FEL beamlines to span the science case





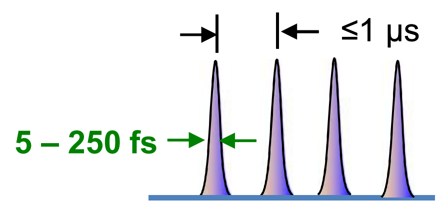
High resolution
~Time-bandwidth limited
10^{11} – 10^{12} ph/pulse
10^{-3} – 5×10^{-5} bandwidth

High-resolution spectroscopy
Diffract-and-Destroy
(with harmonics)



Ultra-fast
Sub-fs pulses
2 color
10^{8} ph/pulse

Multidimensional
spectroscopy



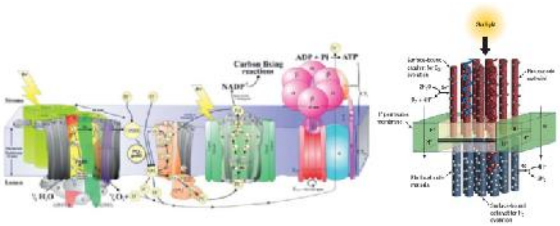
Highest rep rate
High flux
10^{11} - 10^{12} ph/pulse
100 W

Diffract-and-Destroy
(at highest rate)
Photon correlation
spectroscopy

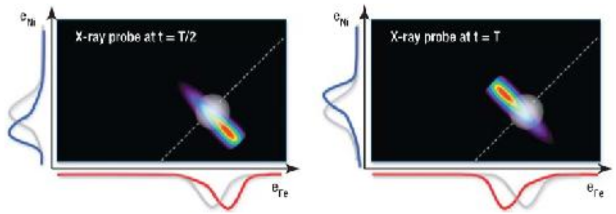
NGLS
next generation light source

Broad Range of Energy Science Uniquely Enabled by NGLS

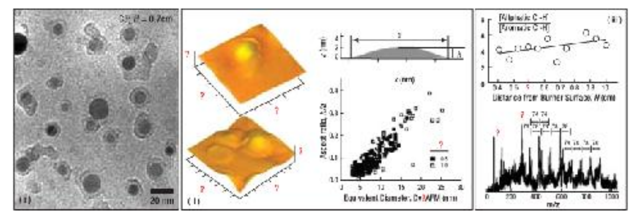
Natural and Artificial Photosynthesis



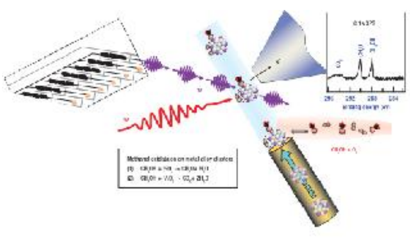
Fundamental Charge Dynamics



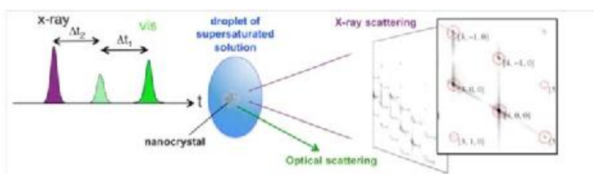
Advanced Combustion Science



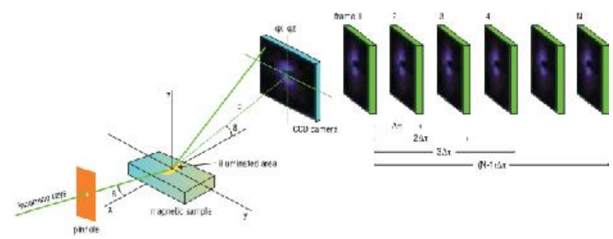
Catalysis



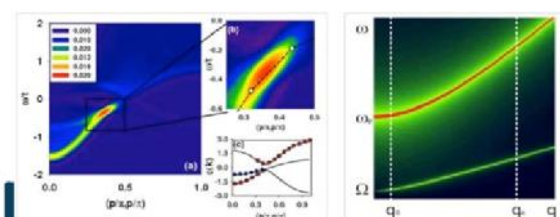
Nanoscale Materials Nucleation



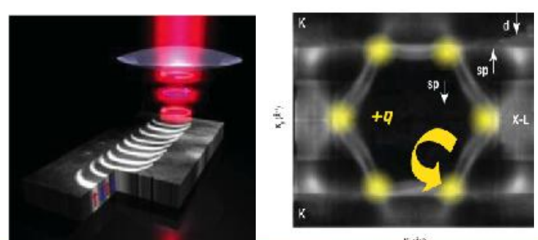
Dynamic Nanoscale Heterogeneity



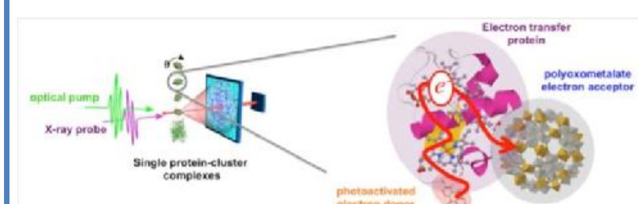
Quantum Materials



Nanoscale Spin and Magnetization

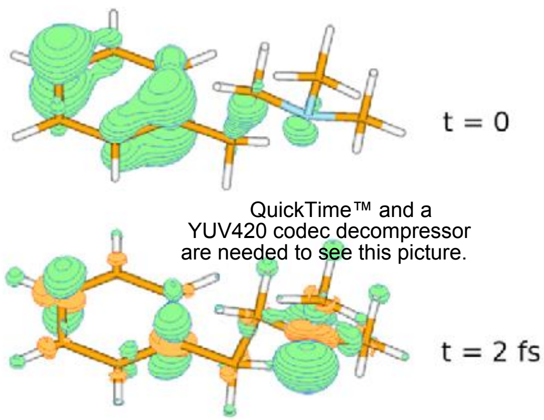


Bioimaging: Structure-to-Function



NGLS - What Does it Do?

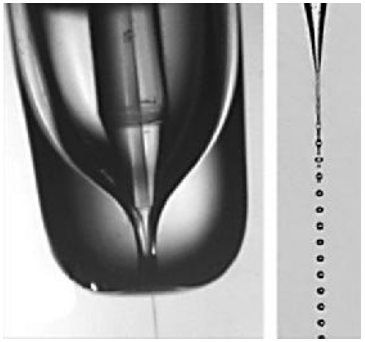
- **High repetition rate X-ray laser with ultrafast pulses**
- **NGLS will probe the *motion* of molecules, atoms, and electrons**
- **On their natural time scales – femtoseconds (fs) and faster….**
- **With unprecedented resolution**
  - ***nanometers (molecules) to Angstroms (atoms)***
- **With chemical sensitivity – Carbon, Oxygen, Nitrogen…..**



Time to do Experiments - Photosynthesis

Required	10^{17}	photons
Damage Limit	10^{8}	ph/pulse
Max Rep. Rate	10^{5}	Hz

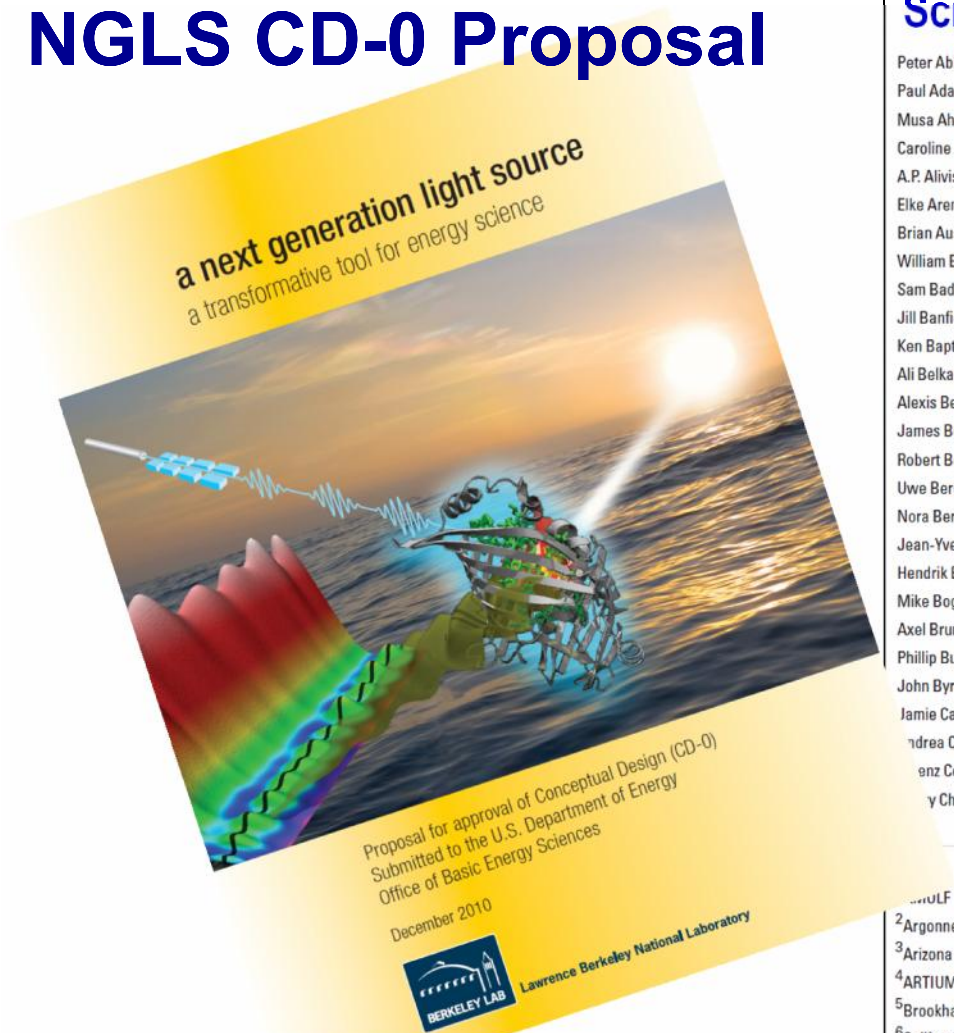
Sample Replacement:
10^{5} Hz



Time to do experiment:
Photons Required / (Photons/Pulse x Rep. Rate)

	Source (*intrinsic*)				
	Max. ph/pulse	Max. Rep. rate [Hz]	**Time to do experiment**		Time resolution
Storage Ring	10^{5}	$5\text{x}10^{8}$	$10^{17}/10^{5}/10^{5}$	**100 days**	100 ps
Pulsed FEL	10^{10}	10^{2}	$10^{17}/10^{8}/10^{2}$	**100 days**	~fs
NGLS	10^{9}	10^{6}	$10^{17}/10^{8}/10^{5}$	**3 hours**	~fs

NGLS CD-0 Proposal



- Submitted December 2010
- More than 150 contributors
- Representing >40 national and international research institutions

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NGLS project status

NGLS
next generation light source

- LBNL submitted a CD-0 proposal in December 2010
- DOE approved "Mission Need" for the Next Generation Light Source
- Currently no DOE budget to pursue a Project
- LBNL is
  - Fully committed to NGLS
  - Performing Accelerator and Detector R&D
  - Performing feasibility studies which will inform a Conceptual Design

The Deputy Secretary of Energy
Washington, DC 20585

April 5, 2011

MEMORANDUM FOR WILLIAM F. BRINKMAN
DIRECTOR
OFFICE OF SCIENCE

FROM: DANIEL B. PONEMAN

SUBJECT: Approval of Critical Decision-0 for the Next Generation Light Source

In accordance with Department of Energy Order 413.3B, *Program and Project Management for the Acquisition of Capital Assets*, the Next Generation Light Source project has met Critical Decision (CD)-0 (Approve Mission Need) requirements. As the Secretarial Acquisition Executive, based on the recommendation of the Energy Systems Acquisition Advisory Board, I approve CD-0. The rough order of magnitude cost range is $0.9 billion to $1.5 billion.

Please continue to work with the Office of Engineering and Construction Management as you progress to Critical Decision-1 (Alternative Selection and Cost Range).

cc:
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Paul Bosco, MA-50
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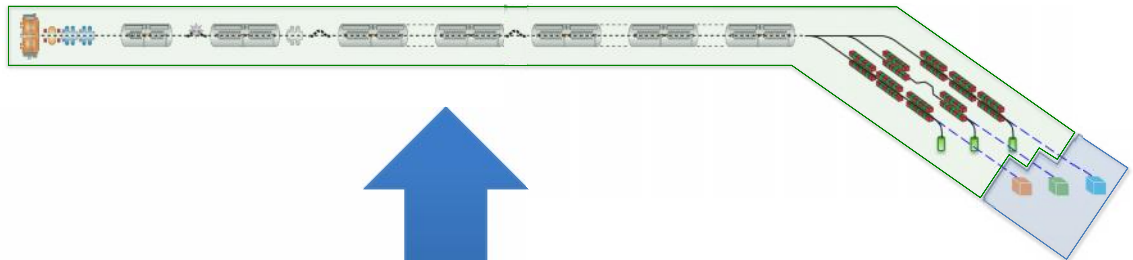
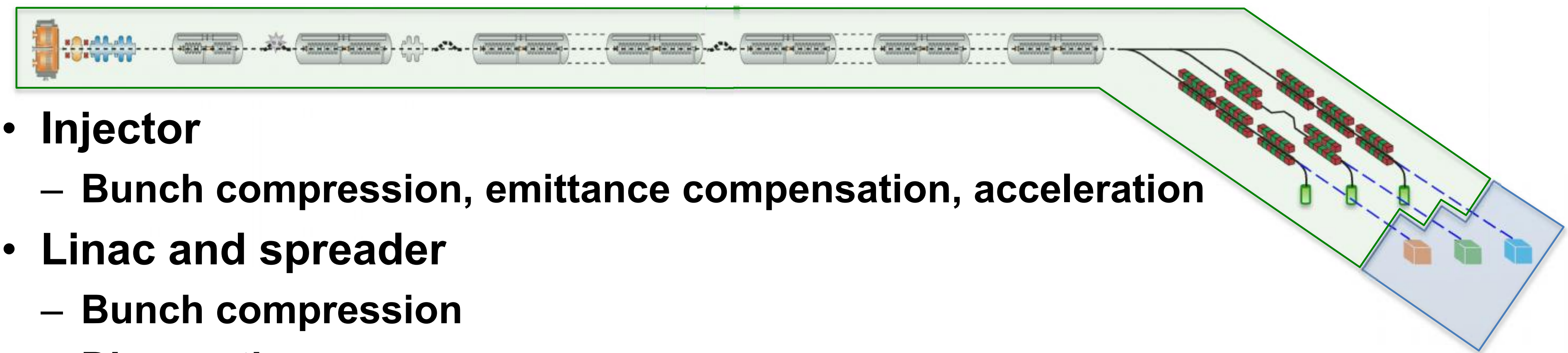
Associate Director, Office of Basic Energy Sciences, SC-22
Director, Office of Project Assessment, SC-28

Science requirements drive machine design



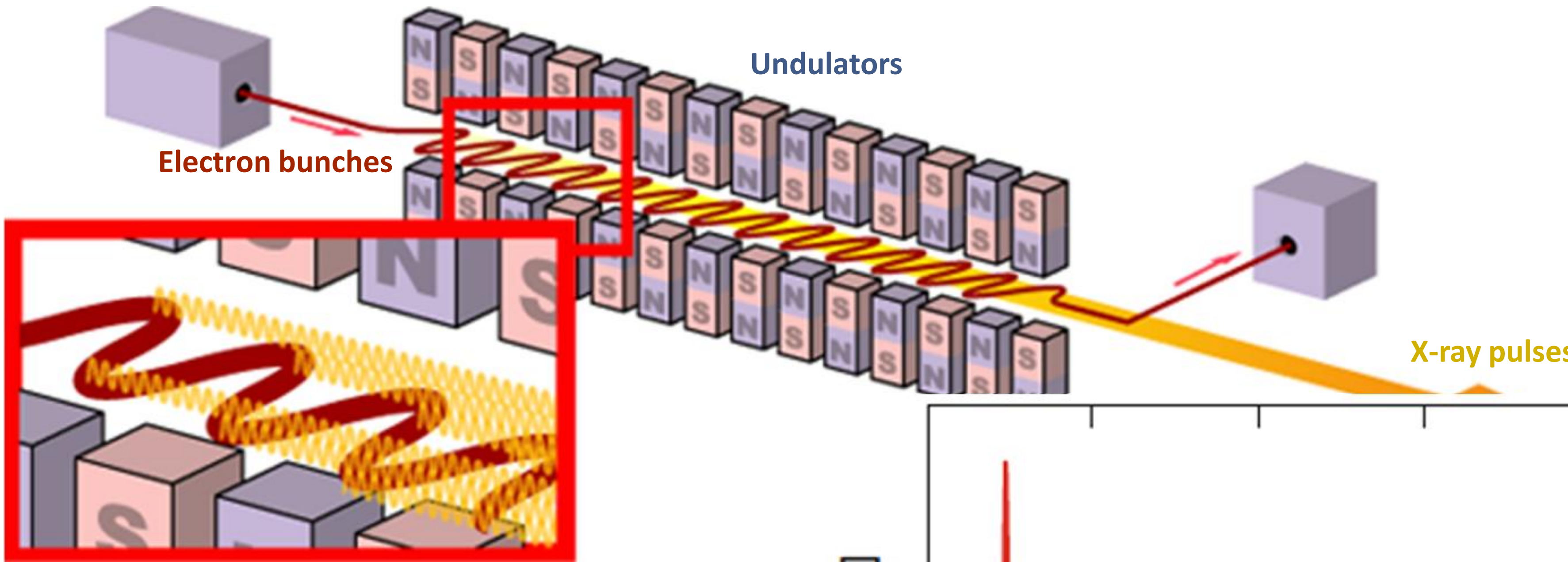
- **Tuning range**
- **Maximum photon energy**
- **Peak flux**
- **Average Flux**
- **Repetition rate**
- **Two-color capability**
- **Pulse duration**
- **Bandwidth**
- **Accuracy**
- **Stability**
- **Synchronization**
- **Contrast ratio**

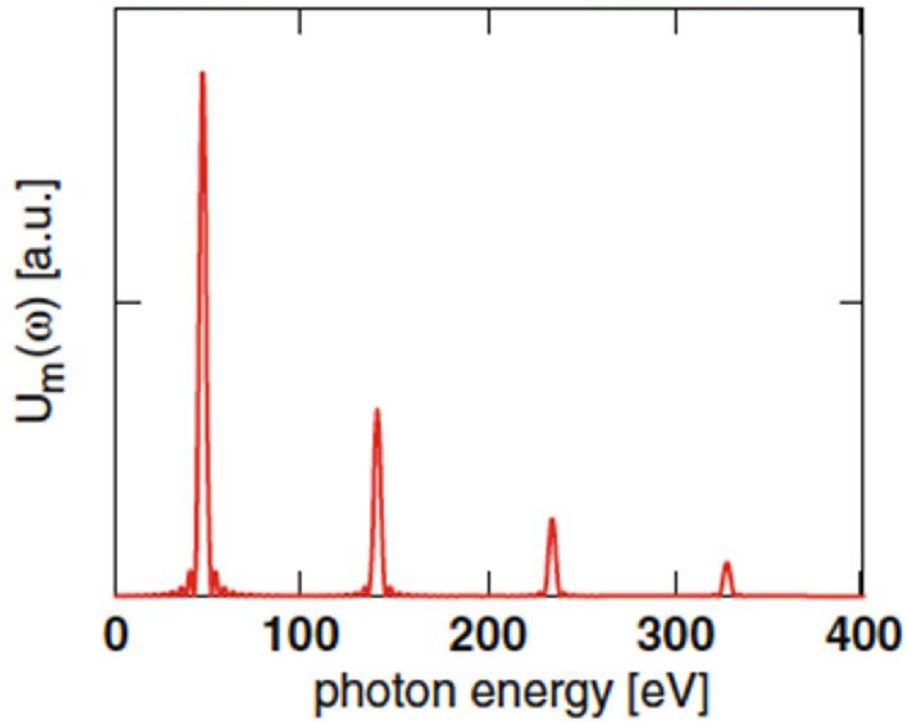
Work in progress to better define the machine layout



- **Injector**
  - Bunch compression, emittance compensation, acceleration
- **Linac and spreader**
  - Bunch compression
  - Diagnostics
  - Cryomodules, accelerating gradient, cavity quality factor, field emission, higher-order-mode power
  - Collimation
  - Kicker and septum magnets, spreader transport lattice
- **FEL design**
  - Undulators
  - Seeding
- **Beam dumps**

Undulator radiation



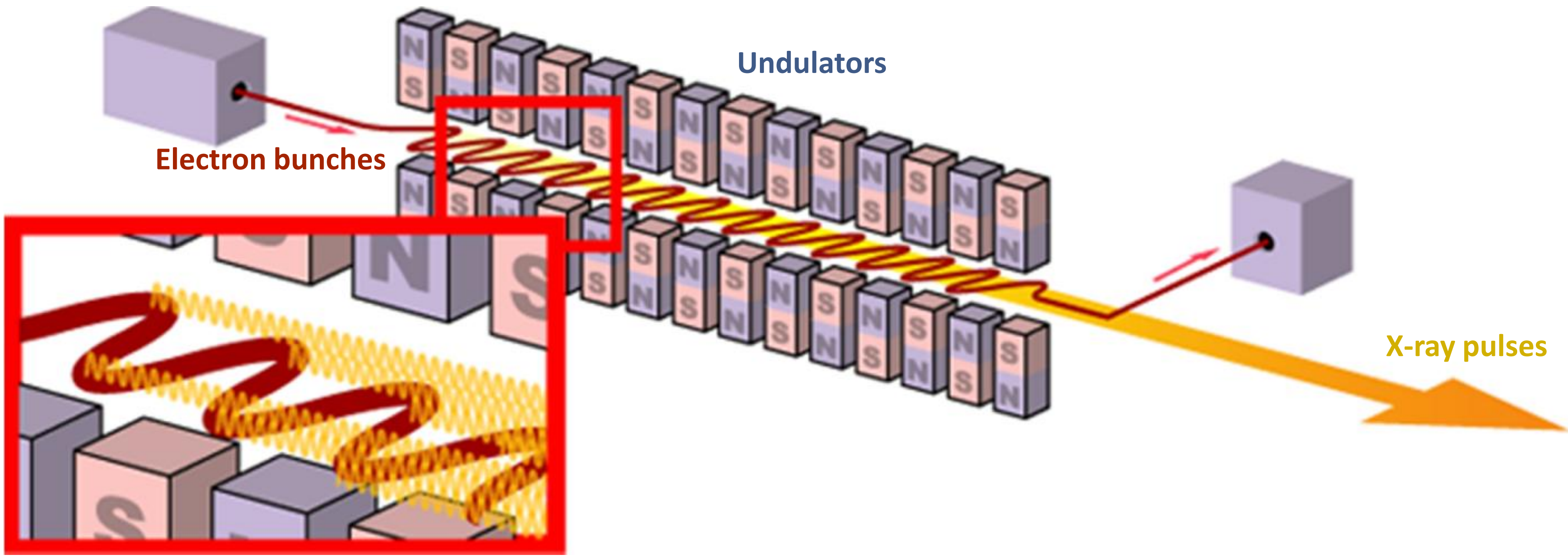


Over one undulator period, the electron is delayed with respect to the light by one optical wavelength

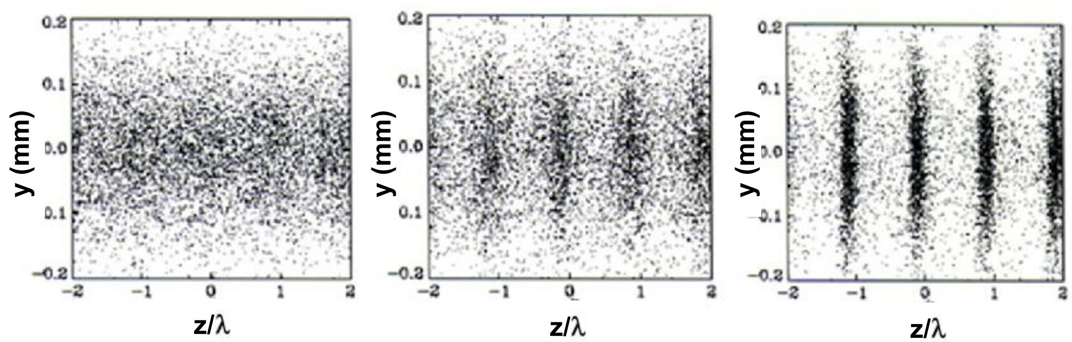
$$\lambda_{x-ray} = \frac{\lambda_{undulator}}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

$$K = \frac{eB_0\,\lambda_{undulator}}{2\pi mc}$$

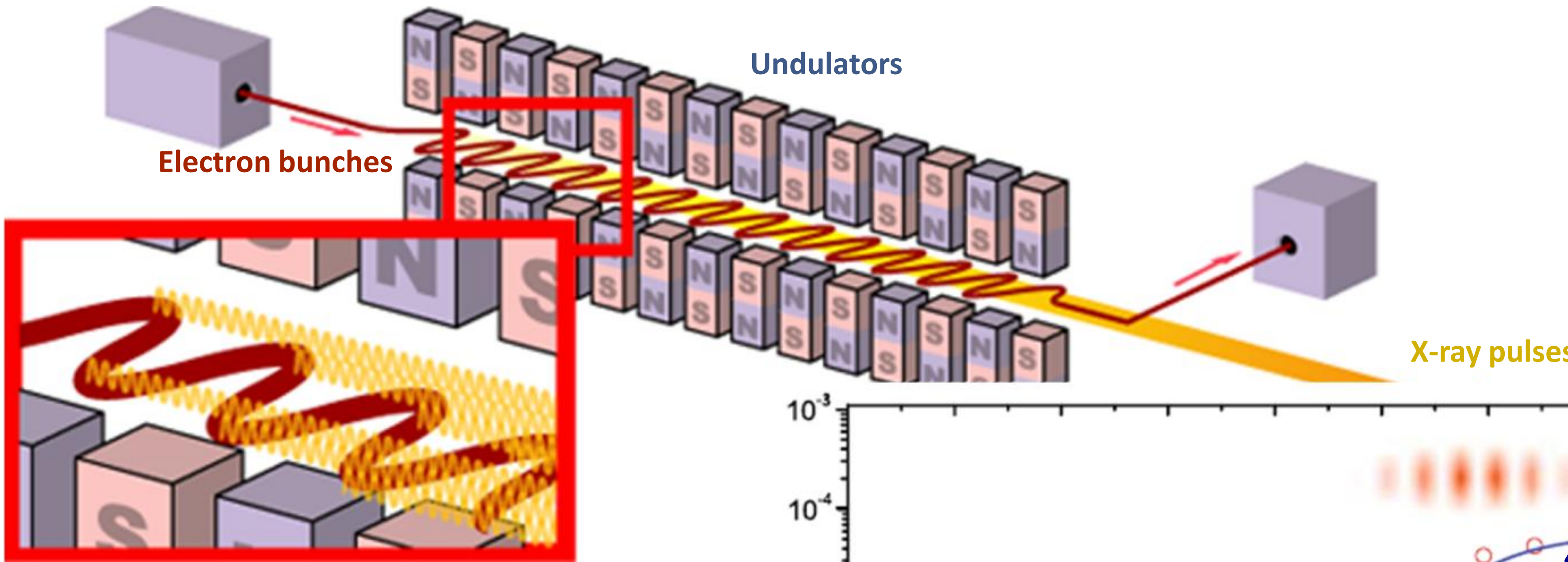
FEL bunching



Microbunching: electrons losing energy to light travel a longer distance than electrons gaining energy from the light

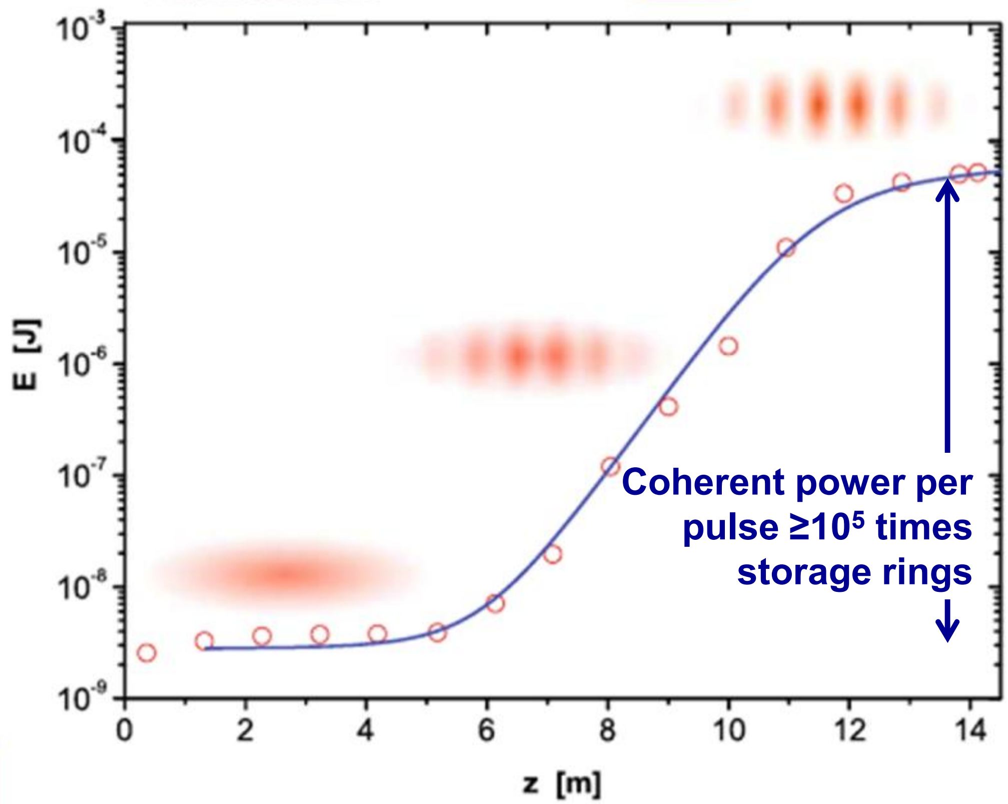


FEL gain

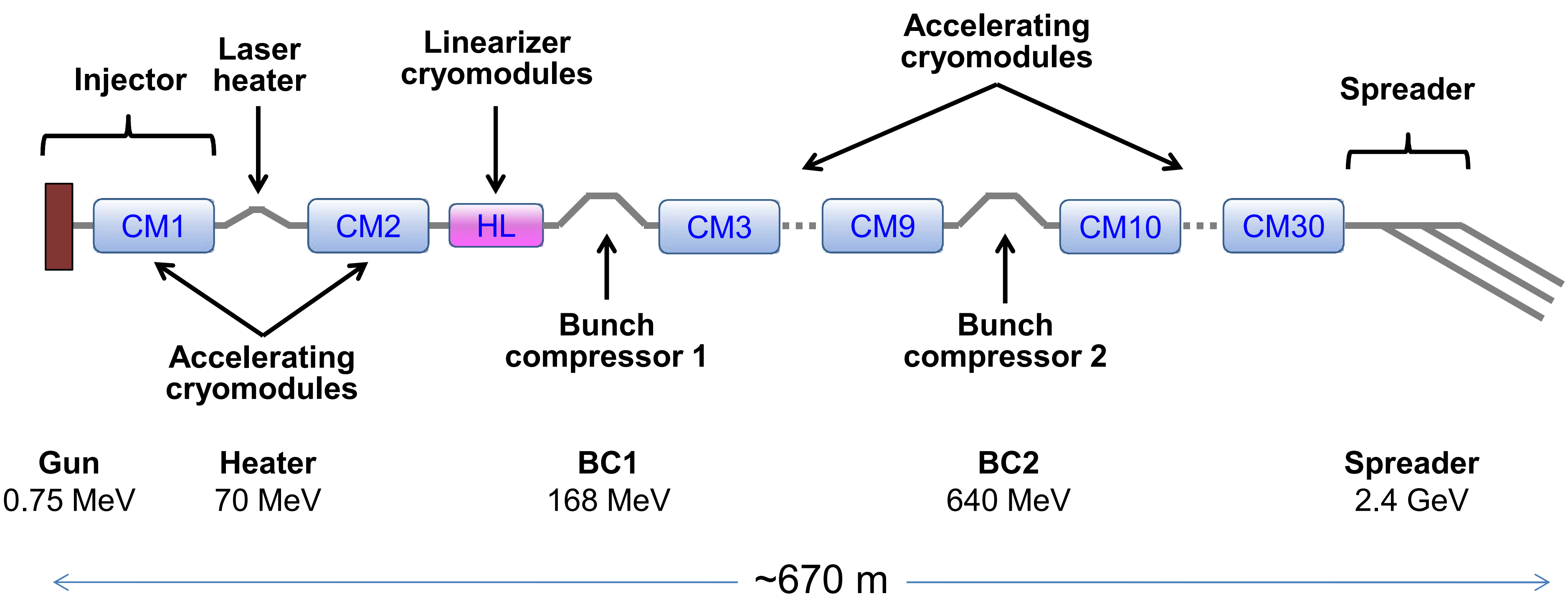


The particles within a microbunch radiate like a single particle of high charge

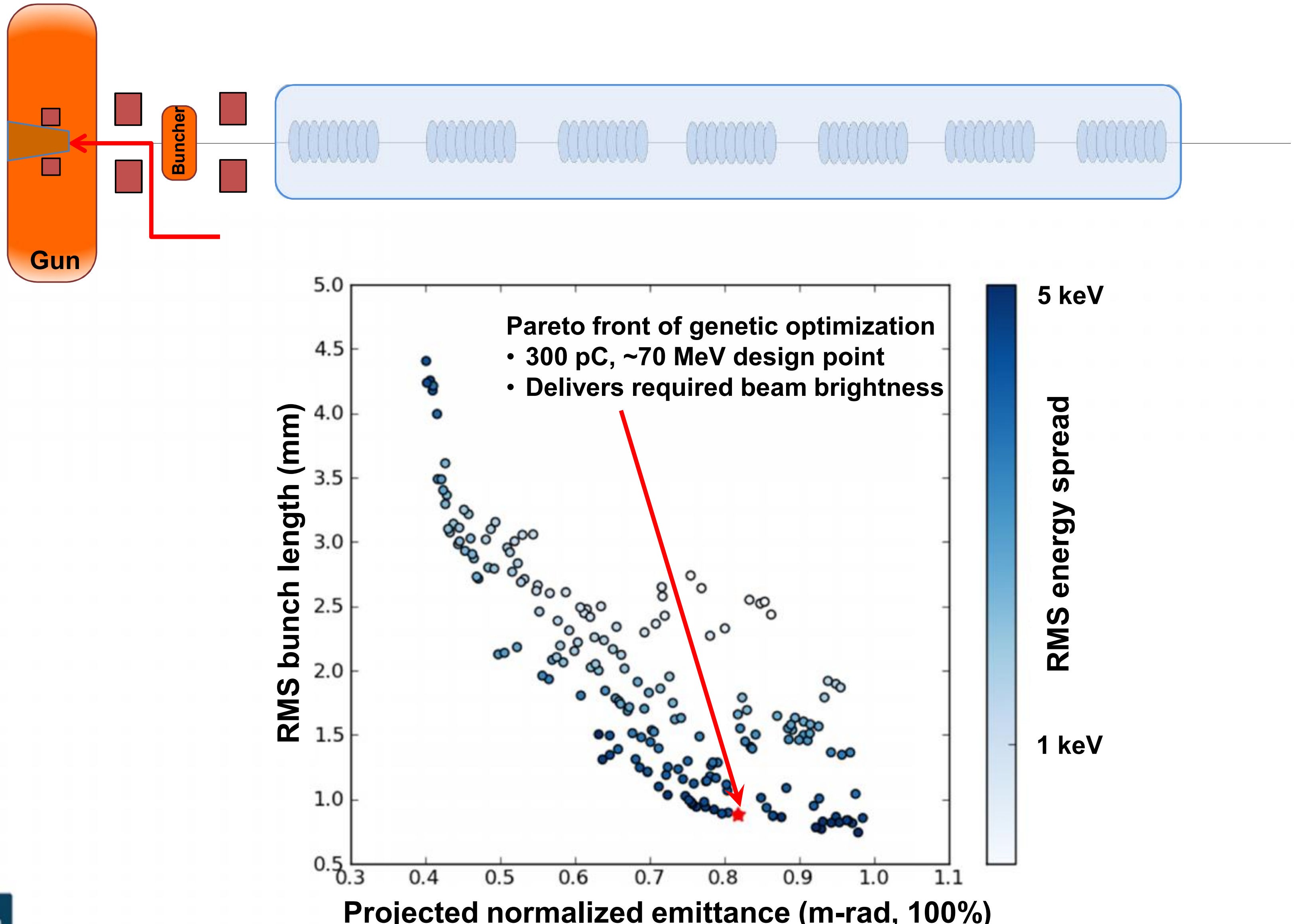
The resulting strong radiation field enhances the microbunching even further and leads to an exponential growth of the radiation power



Linac schematic layout



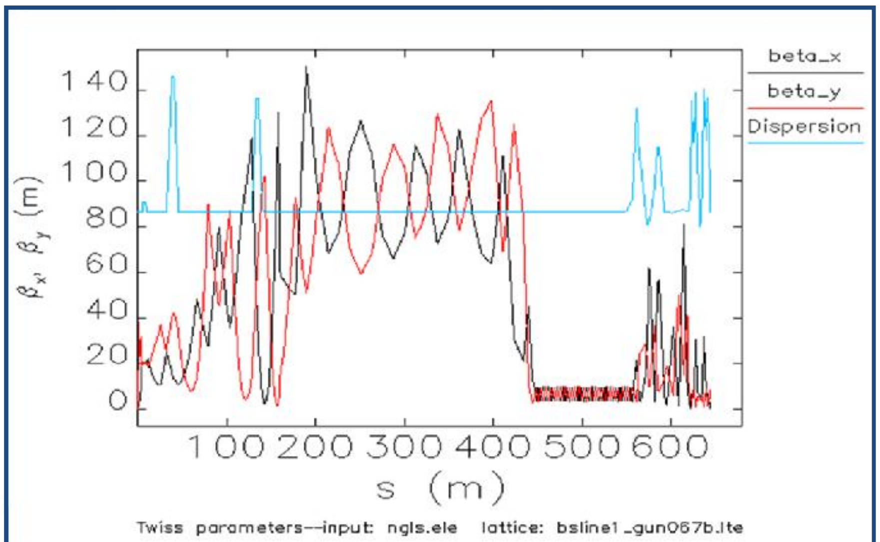
Injector multivariate optimization



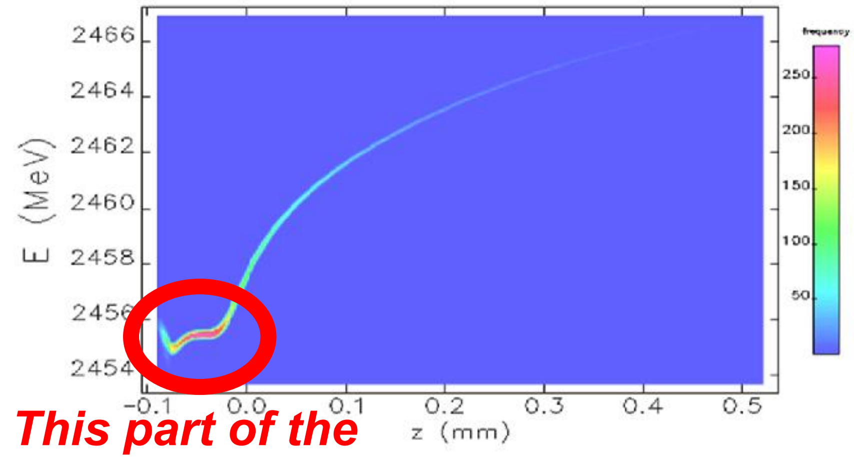
Beam dynamics modeling through linac

- Two-stage compression
- 2.4 GeV
  - APEX-gun generated beams (300pC)
  - ≥ 600 A peak current and small residual energy chirp within usable beam core
  - limited CSR-induced projected emittance growth

Twiss functions through the Linac

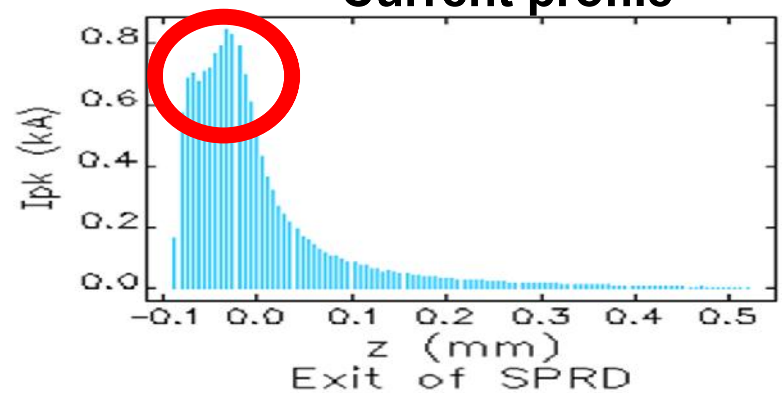


Longitudinal beam phase-space at entrance of FEL beamlines*



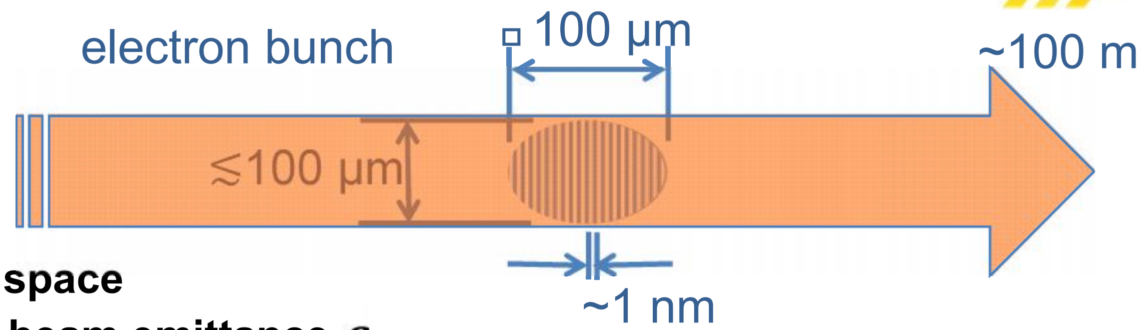
This part of the bunch lases

Current profile



**'Elegant' simulation through the linac starting from an ASTRA-simulated beam out of the APEX-gun based injector*

Physics & technology challenges



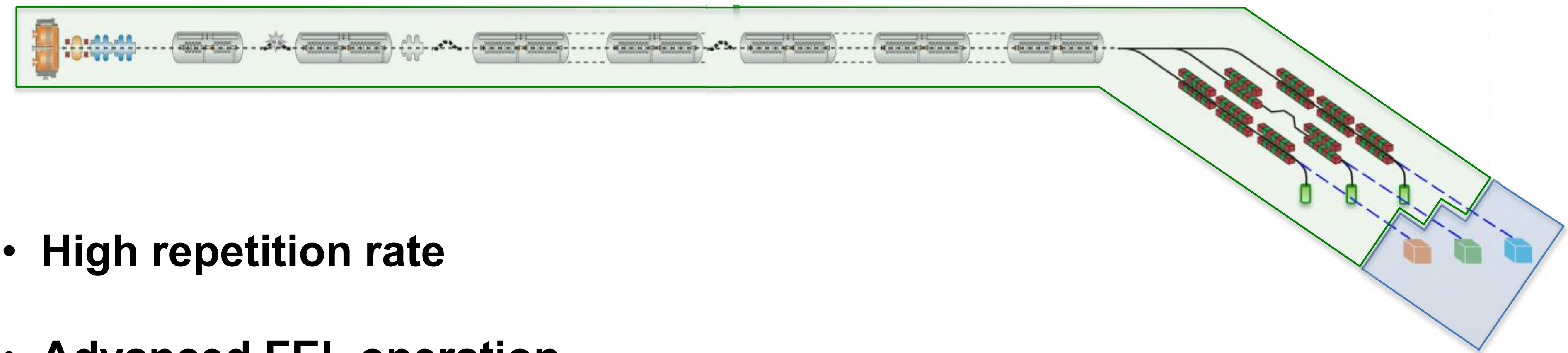
- **Transverse phase space**
  - **Small electron beam emittance ε**
- **Longitudinal phase space**
  - **Large peak current I_{peak}**
  - **Small energy spread σ_E**
- **Electron beam energy γ**
  - **High gradient accelerator**
- **Short period undulators**
- **Collective effects**
- **Average power**
  - **High repetition rate injector**
  - **CW superconducting accelerator**
- **X-ray temporal control**
  - **FEL design & seeding techniques**

$$\frac{\varepsilon_n}{\gamma} \approx \frac{\lambda_{x-ray}}{4\pi}$$

Power/ undulator length $\sim f\left(I_{peak}, \frac{\varepsilon_n}{\gamma}, \sigma_E\right)$

$$\lambda_{x-ray} = \frac{\lambda_{undulator}}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

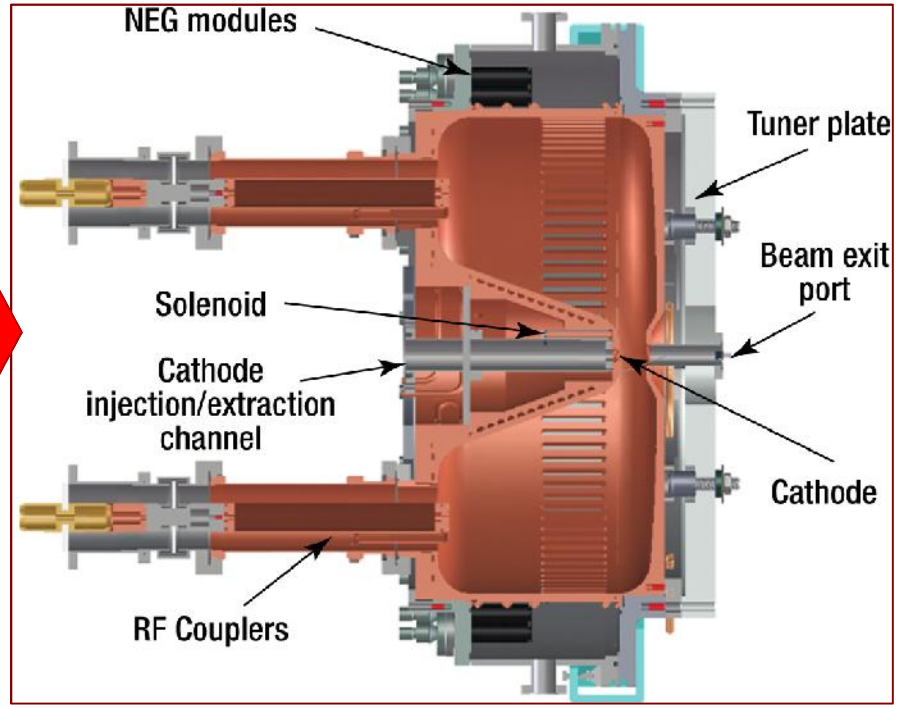
Accelerator Systems R&D



- High repetition rate
- Advanced FEL operation
- High average power
- Superconducting accelerator developments

Injector design goals – APEX gun

- Repetition rate 1 MHz
- Charge per bunch from ~10 pC to ~1 nC
- Emittance <10^{-6} mm-mrad (normalized)
- Electric field at the cathode ≥~10 MV/m (space charge emission limit)
- Beam energy at the gun exit ≥~500 keV (space charge control)
- Bunch length ~100 fs to ~10 ps for handling space charge effects, and for allowing different modes of operation
- Compatible with magnetic field control within the gun (emittance exchange and compensation)
- 10^{-11} Torr vacuum capability (cathode lifetime)
- Accommodates a variety of cathode materials
- High reliability for user operations



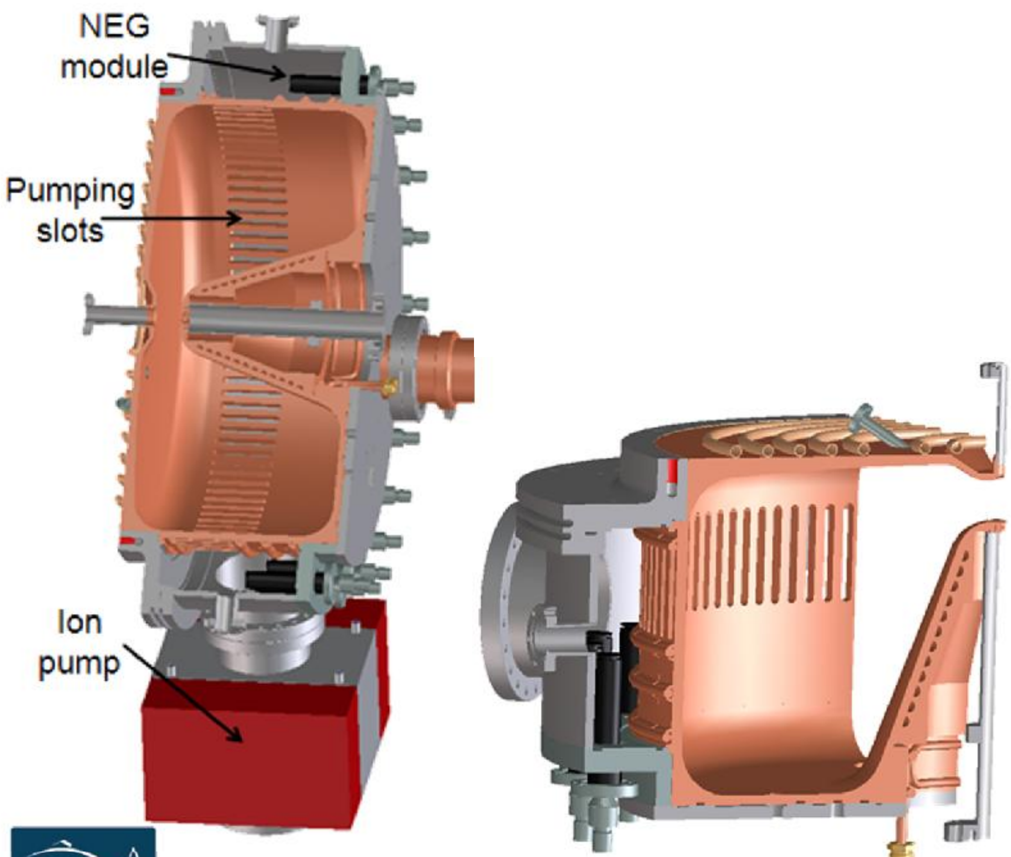
The gun is the most challenging component
LBNL approach uses a CW VHF cavity

APEX gun

VHF cavity operates in CW mode

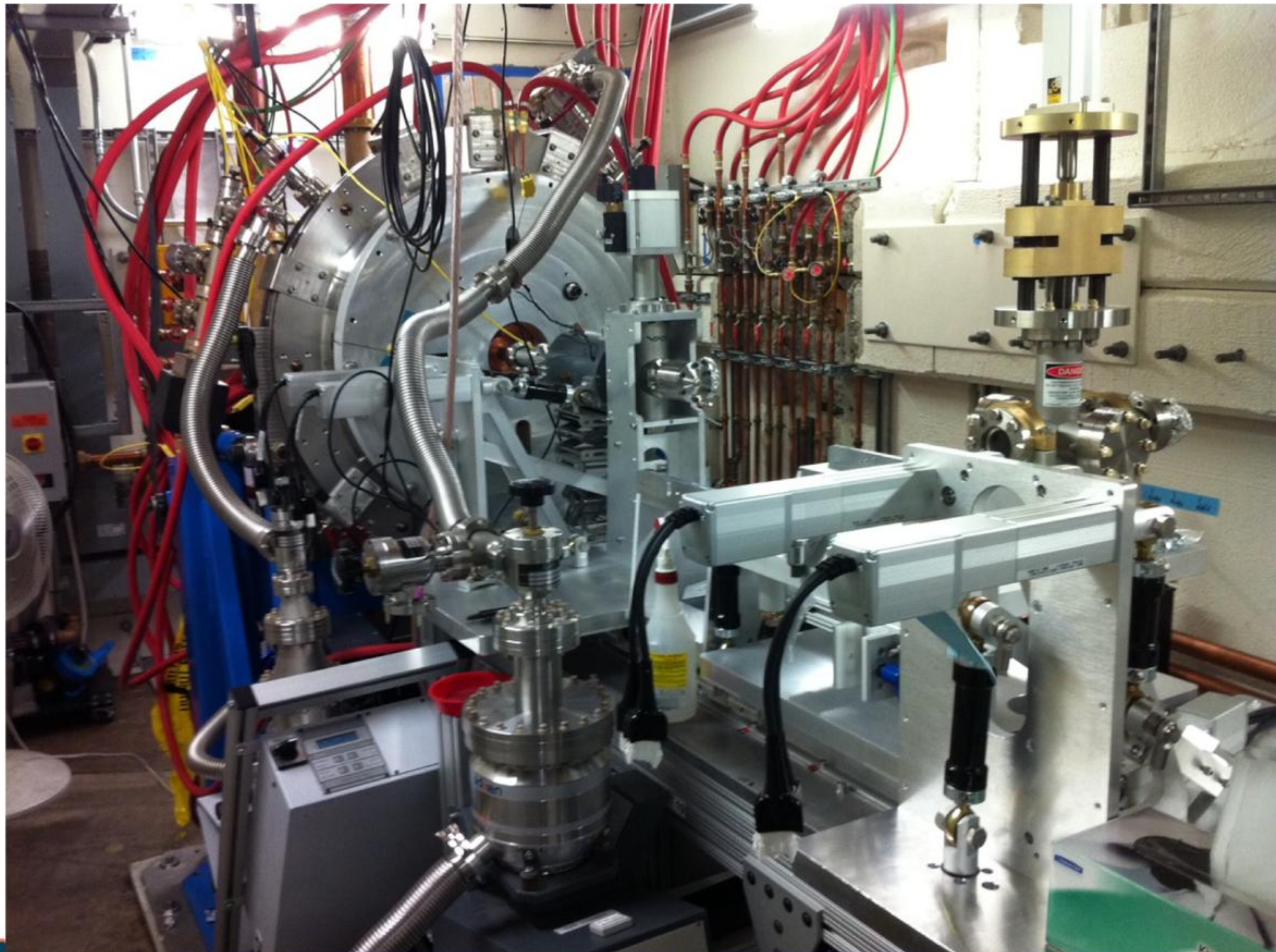
- **Low power density on cavity walls**
- **High conductance vacuum slots**
- **High gradient at cathode**

Frequency	187 MHz
Operation mode	CW
Gap voltage	750 kV
Field at the cathode	19 MV/m
Q_0	30887
Shunt impedance	6.5 MΩ
RF Power	90 kW
Stored energy	2.3 J
Peak surface field	24 MV/m
Peak wall power density	25 W/cm^2
Accelerating gap	4 cm
Diameter/Length	70/35 cm
Operating pressure	< 10^{-11} Torr

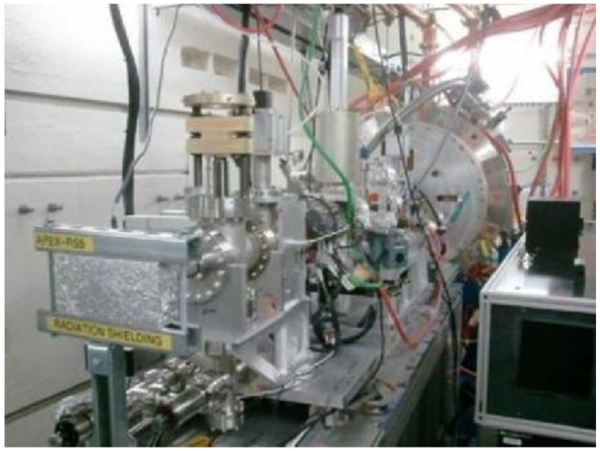


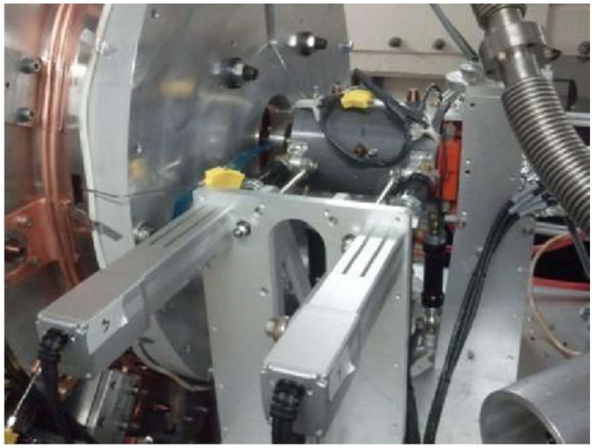
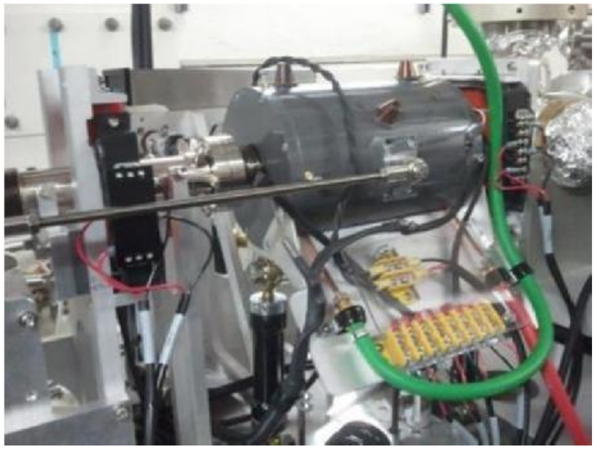
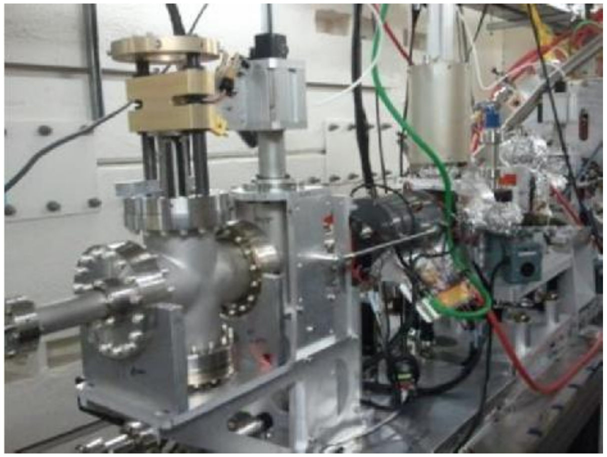
APEX gun in test area

- **APEX cavity is successfully RF conditioned**



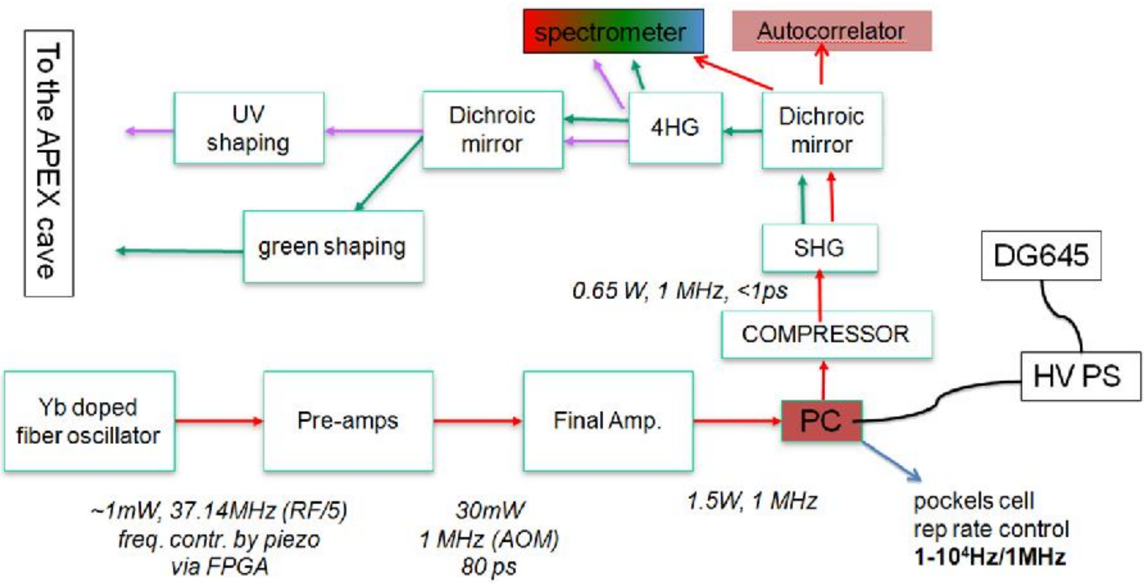
APEX in the Beam Test Facility

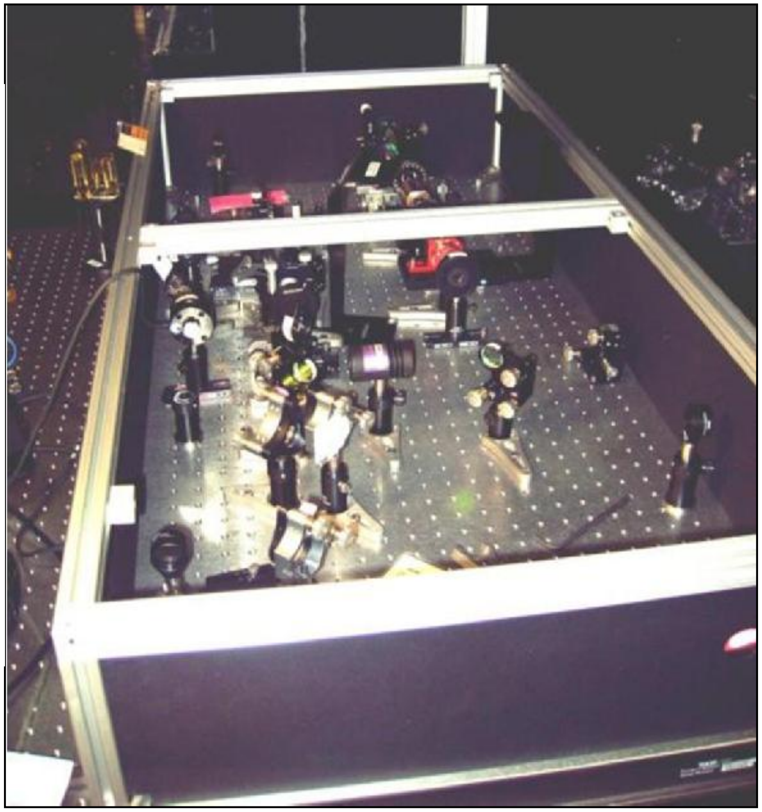



Yb fiber photocathode drive laser

- **1 MHz reprate Yb fiber laser**
  - **LLNL/UCB/LBNL collaboration**





Photocathode materials

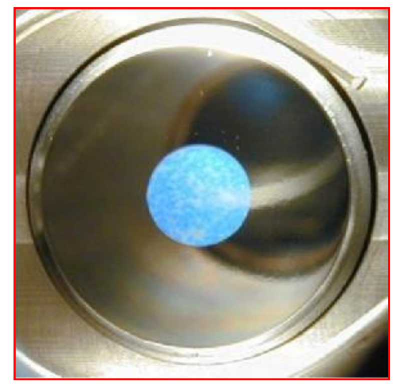
NGLS next generation light source

Alkali Antimonides eg. K_2CsSb

- Fast
- Reactive; requires UHV ~10^{-10} Torr pressure
- High QE (typically >5%)
- No pulse charge saturation
- Requires green light (532 nm, 2nd harm. conversion from IR)
- For 1 nC & 1 MHz rep-rate, ~ 1 W IR required
- Unproven lifetime at high rep-rate and high average current

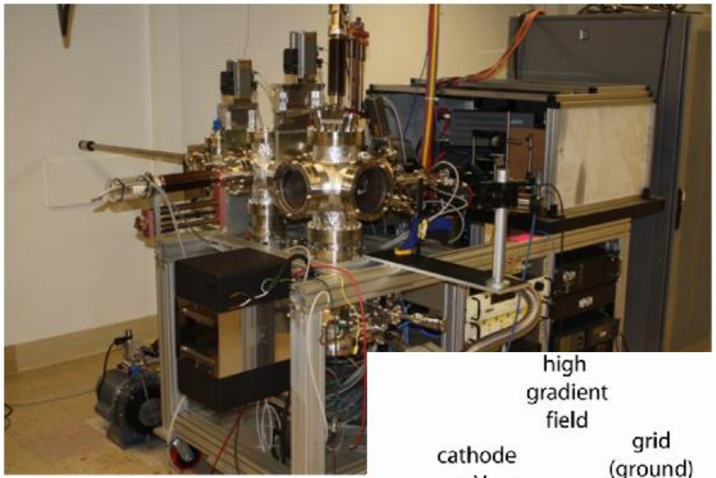
Cs_2Te (developed by INFN/LASA and delivered to LBNL)

- Fast
- Relatively robust and un-reactive (~10^{-9} Torr)
  - Demonstrated in a high gradient rf gun
- High QE (typically >5%)
- No pulse charge saturation
- Requires UV 250 nm, 3rd or 4th harm. from IR laser)
- For 1 nC - 1 MHz reprate, ~ 10 W IR required
- Unproven at high rep-rate and high average current

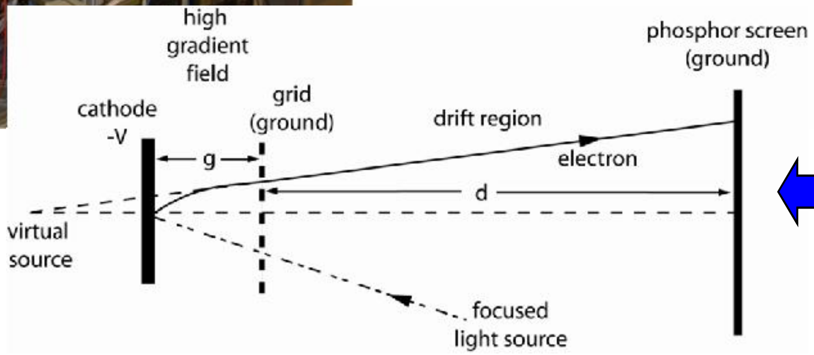


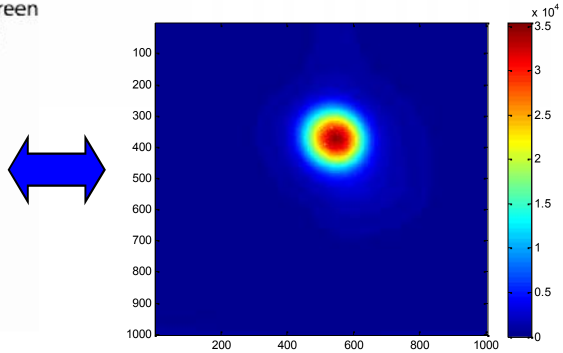
The APEX gun will also be used to test the BNL diamond amplifier cathode

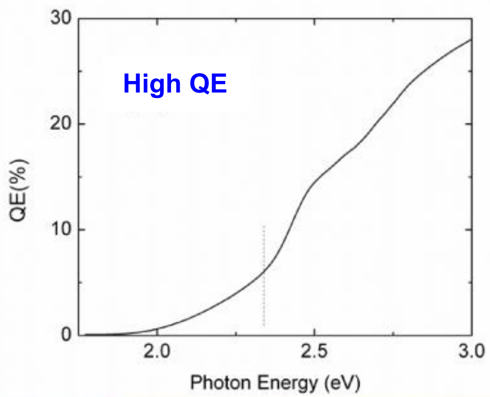
Photocathode materials R&D

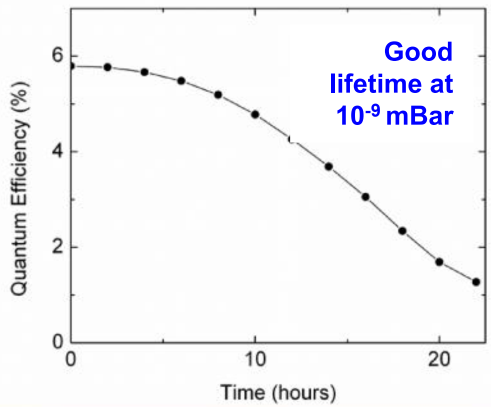


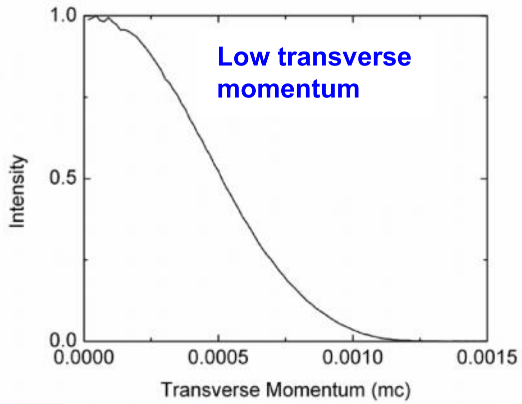
K_2CsSb:
6% QE at 532 nm
0.36 microns / mm rms ε_n
>> 1 week lifetime









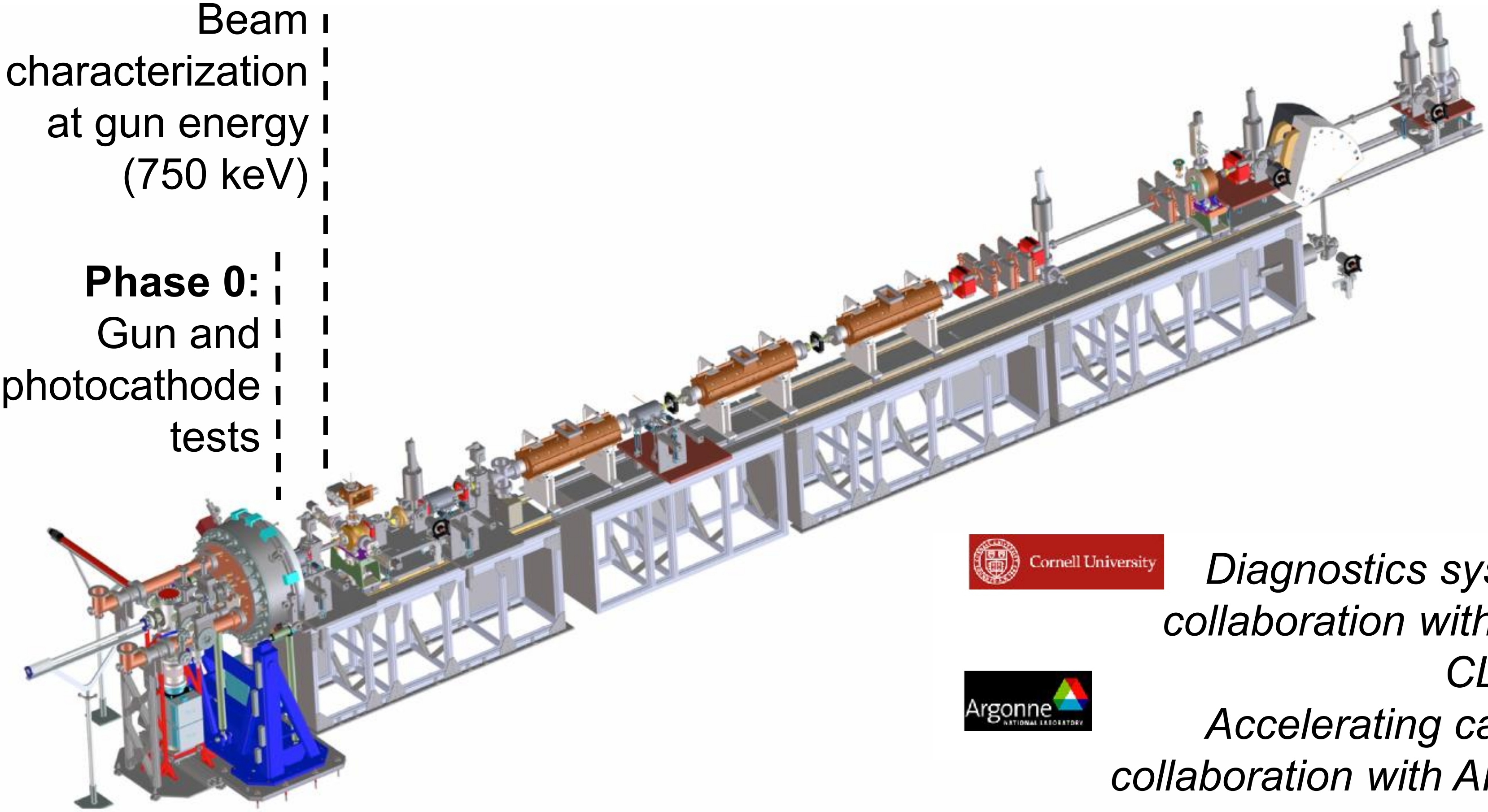


APEX stages

Phase-II:
Beam characterization at 15–30 MeV
- 6-D brightness measurements

Phase I:
Beam characterization at gun energy (750 keV)

Phase 0:
Gun and photocathode tests



Diagnostics systems in collaboration with Cornell CLASSSE

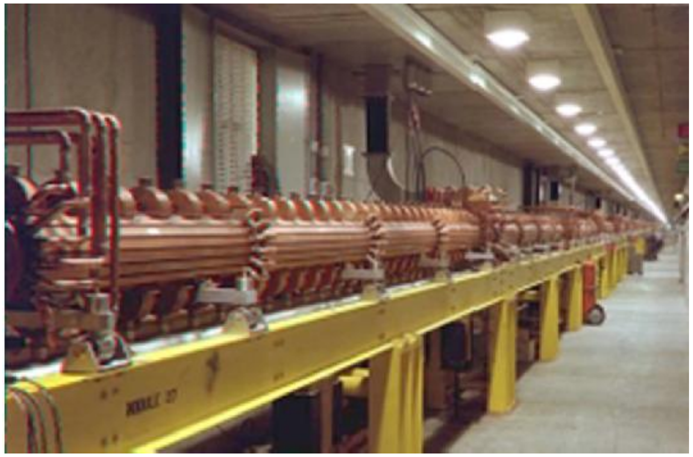
Accelerating cavities in collaboration with ANL AWA

- **Planning for final installation in 2013**

Accelerating structures

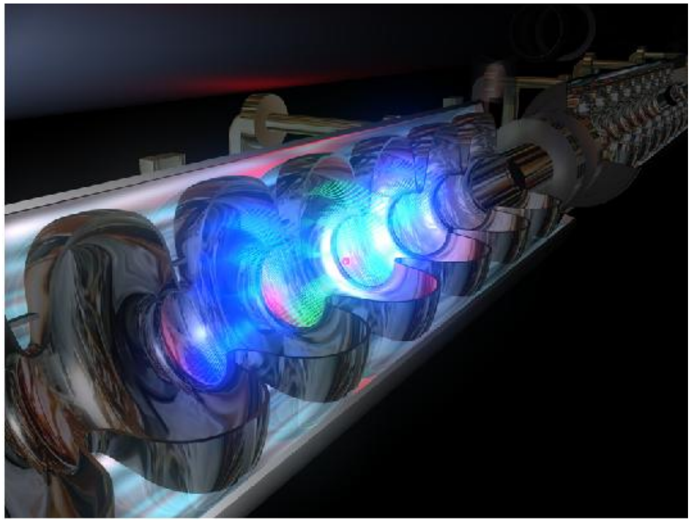
Normal conducting

- **High power dissipation in structure walls**
  - **Operate in pulsed mode for highest gradient**
    - **E.g. 120 Hz SLAC linac (2.9 GHz)**
    - **~ 20 MVm^{-1}**

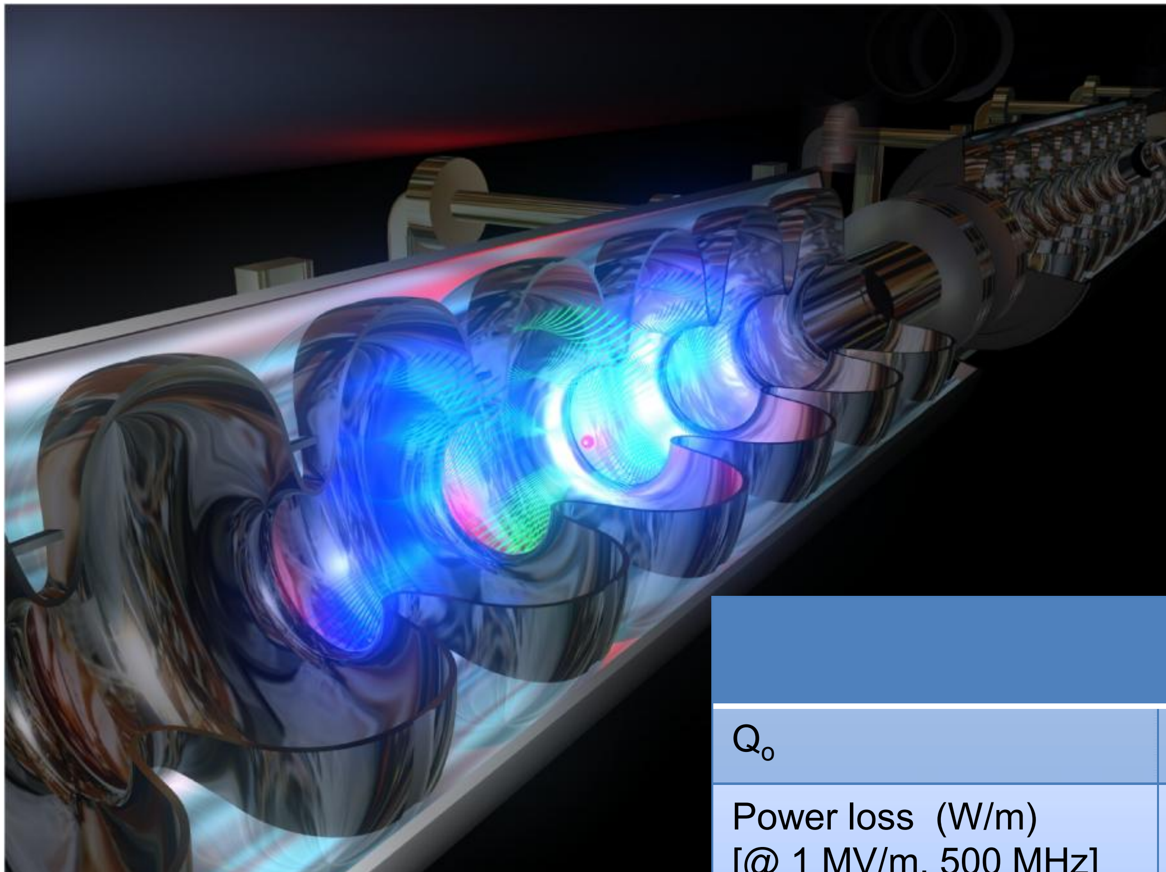


Superconducting

- **Capability to operate CW at high gradient**
  - **Options for beam recirculation and energy recovery**
  - **□ 20 MVm^{-1} a goal for CW operations**
  - **CEBAF 12 GeV upgrade**



A superconducting accelerator is efficient for high repetition-rate beam

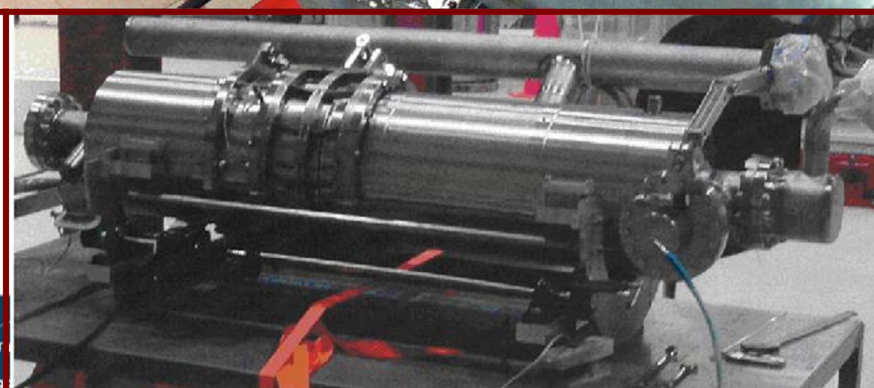


$$R_S = \frac{A}{T} f^2 e^{-\frac{D(T)}{kT}} + R_0$$

	Superconducting	Normal conducting
Q_o	**$2\text{x}10^9$**	**$2\text{x}10^4$**
Power loss (W/m) [@ 1 MV/m, 500 MHz]	**1.5**	**56,000**
Wall-plug power (kW/m) [@ 1 MV/m, 500 MHz]	**0.54**	**112**

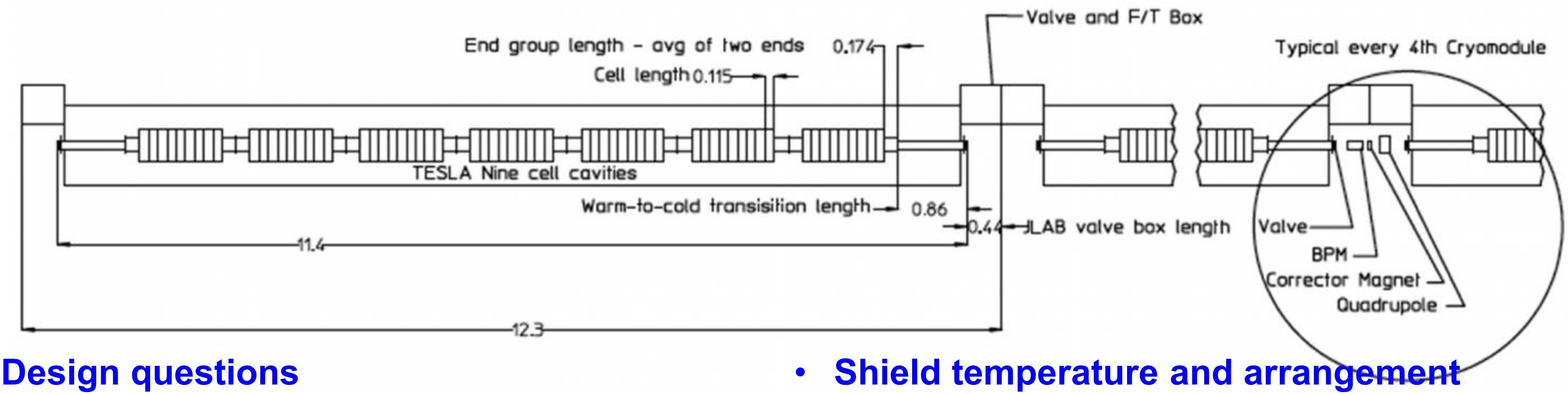
Power requirement reduced by ~200

SCRF cryomodules are mature technology



NGLS cryomodule concept

- **Current cryomodule concept uses “TESLA” cavities in JLAB-style housing**
  - **Cold/warm transitions on each cryomodule**
  - **Distribute 5 K liquid, cool to 1.8 K at cryomodule**
  - **Warm magnets & diagnostics**

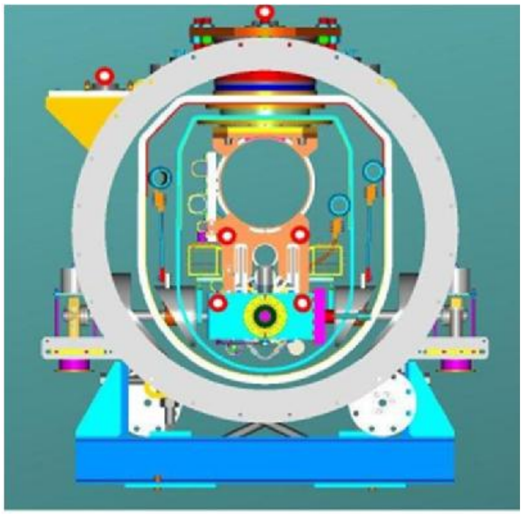


Design questions

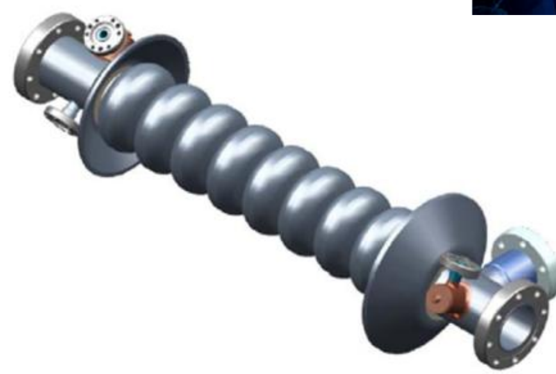
- **Operating gradient increased to ~16 MV/m**
- **$Q_0 \geq 2x10^{10}$**
- **HOM power dissipation and absorption**
- **Field emission**
- **Number of cavities within a single module**
- **Shield temperature and arrangement**
- **Power coupler design**
- **Tuner type and access**
- **Selection and sizing of cryogenic circuits**
- **Minimization of acoustic noise**
- **Warm to cold transitions**

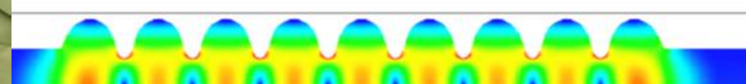
Cryomodules (harmonic cavities)

- **Fermilab cryomodules installed at FLASH**
  - **Modify for CW operation?**



TM_{010} Cavity



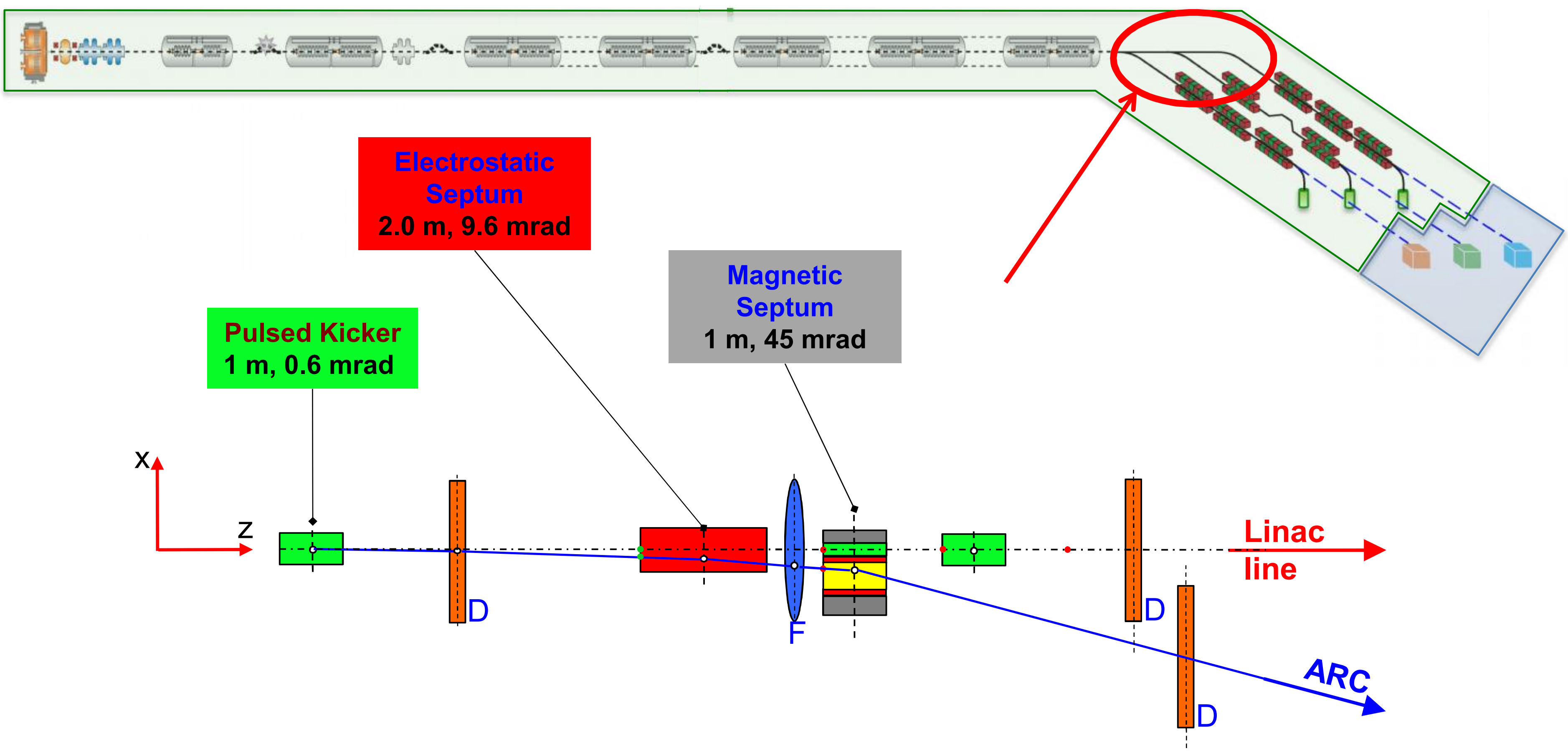


- Decreased surface fields in end cells
- Regular cells -30mm iris diameter
- End-cells iris from the tube side increased up to 40mm for better coupling with the power coupler
- Two HOM couplers are mounted in both ends
- Ports for power coupler and pick-up antenna
- 2.8 mm bulk niobium

Parameter List for 3.9 GHz cavity:

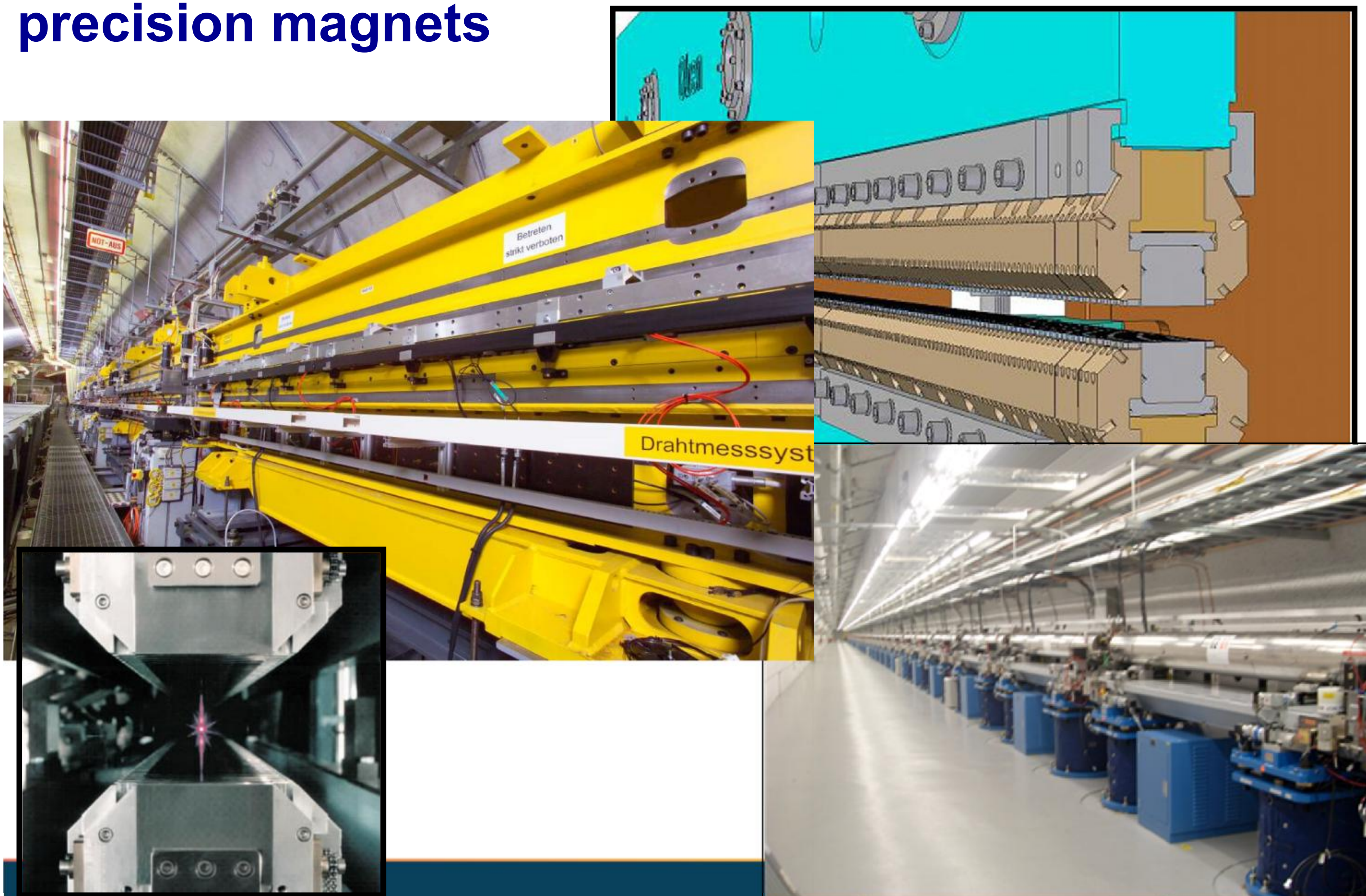
Number of cavities	4
Active Length	0.346 m
Gradient	14 MV/m
Phase	-179 deg
R/Q	375 Ω
E_{peak}/E_{acc}	2.26
B_{peak} (E_{acc}=14 MV/m)	68 mT
Qext	$9.5\cdot10^5$
BBU threshold, Q	<1.e+5
Total energy	20 MeV
Beam current	9 mA
Forward Power	11.5 kW
Power in Coupler	45 kW

Optimizing the beam spreader



- Electrostatic septum allows 5x weaker kickers (1/5 stability tolerance)
- Footprint reduced ~1/3

The FEL undulators are large arrays of precision magnets

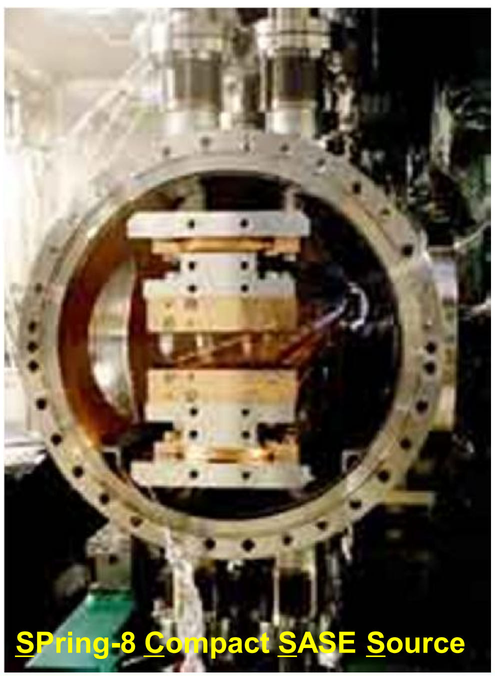


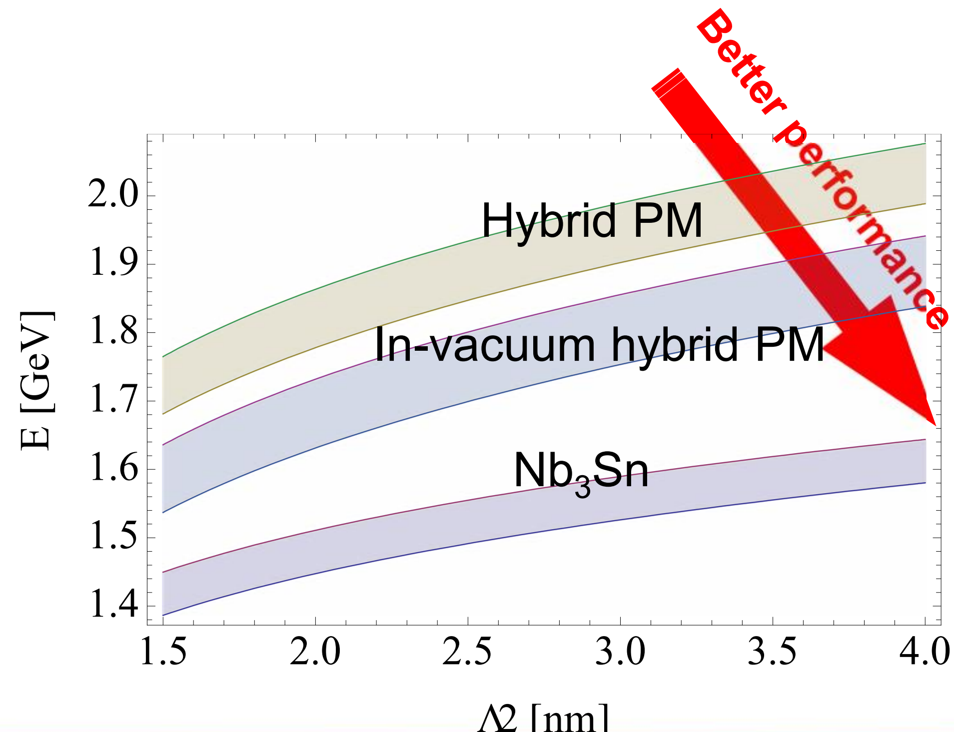
Undulator technology

- **Currently undulator technology limits period □ 15 mm**
- **Requires beam energy ~2 GeV to radiate at 1 nm**
- **Superconducting devices could provide significant performance improvements**
  - **R&D projects under way to develop short-period undulators using Nb_3Sn**

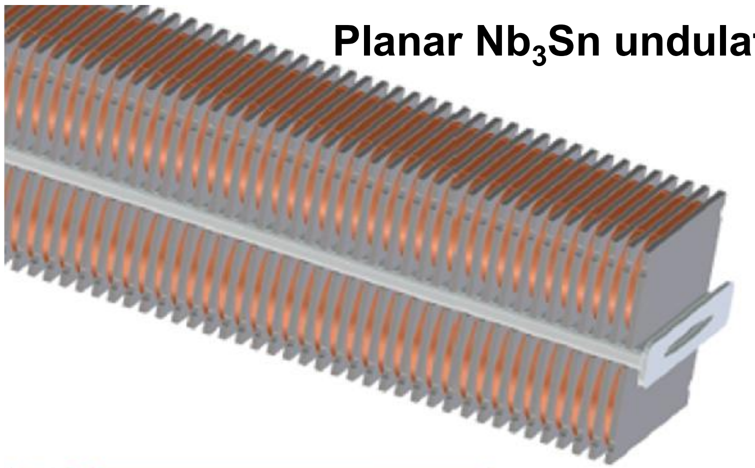
$$\lambda_{x\text{-}ray} = \frac{\lambda_{undulator}}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

$$K = \frac{eB_0\,\lambda_{undulator}}{2\pi mc}$$

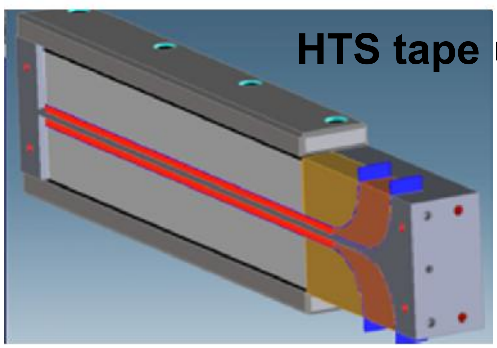

SPring-8 Compact SASE Source



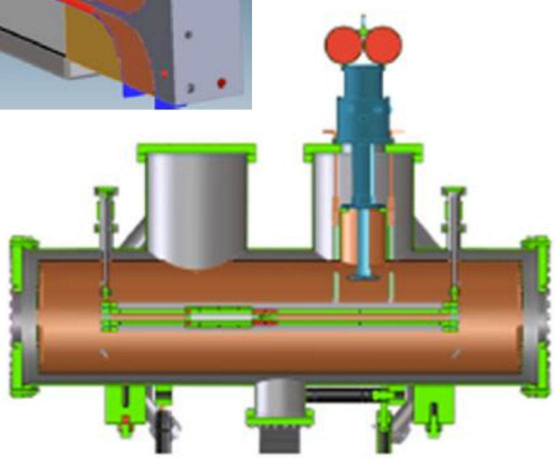
Superconducting undulator R&D



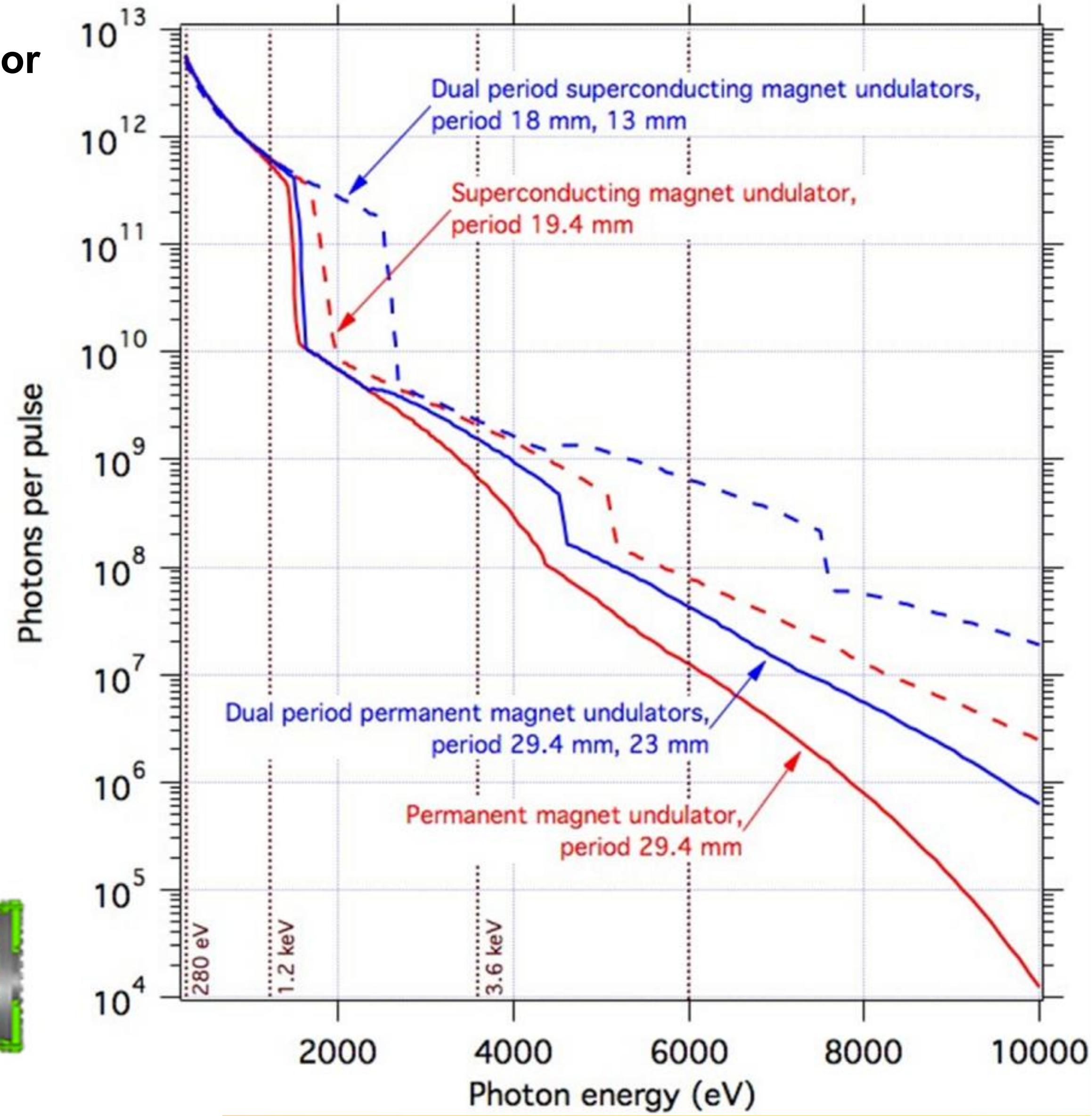
Planar Nb_3Sn undulator



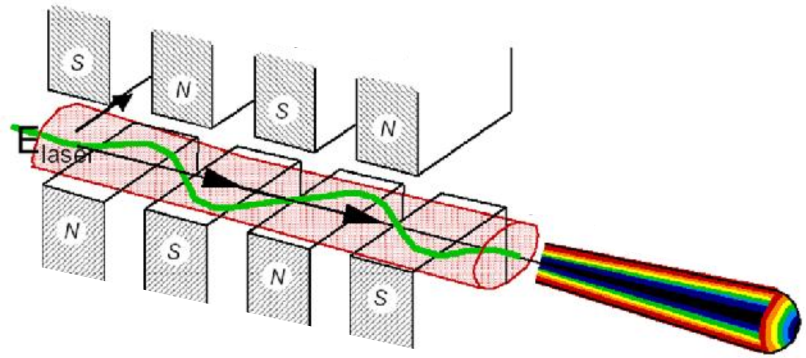
HTS tape undulator

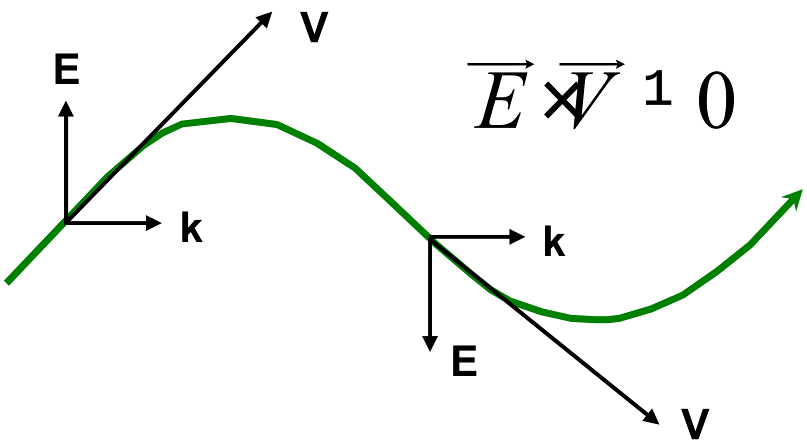


Cryostat for test and measurement



Seeded FELs - 1





$$\vec{E} \times \vec{V} \neq 0$$

Wiggler period

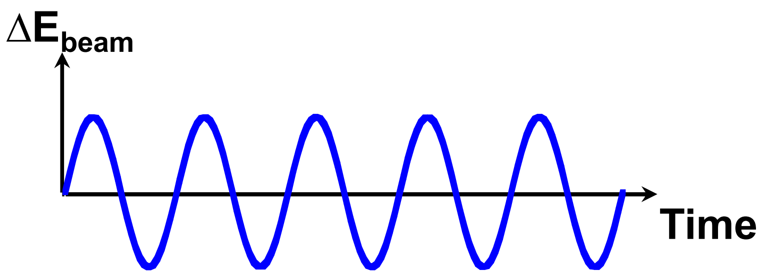
Undulator parameter

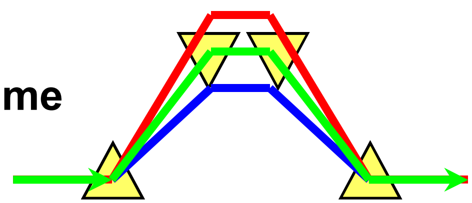
$$\lambda_w = 2\gamma^2 \lambda_L / \left(1 + \frac{K^2}{2}\right)$$

Laser wavelength

- **Electron beam couples to E-field of laser when co-propagating in an undulator**
- **Over one undulator period, the electron is delayed with respect to the light by one optical wavelength**

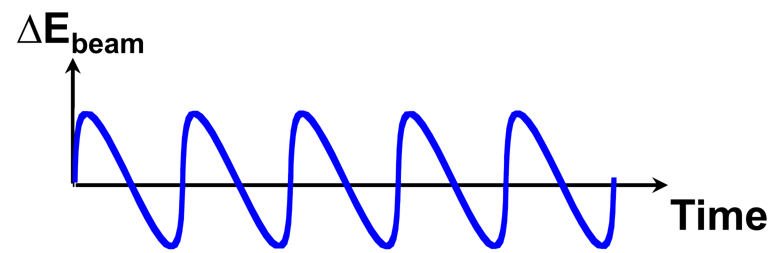
Seeded FELs - 2



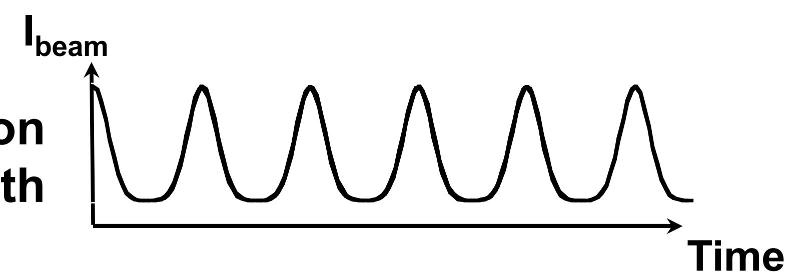


Energy-dependent path length

$$\Delta z = R_{56}\frac{\Delta E}{E}$$



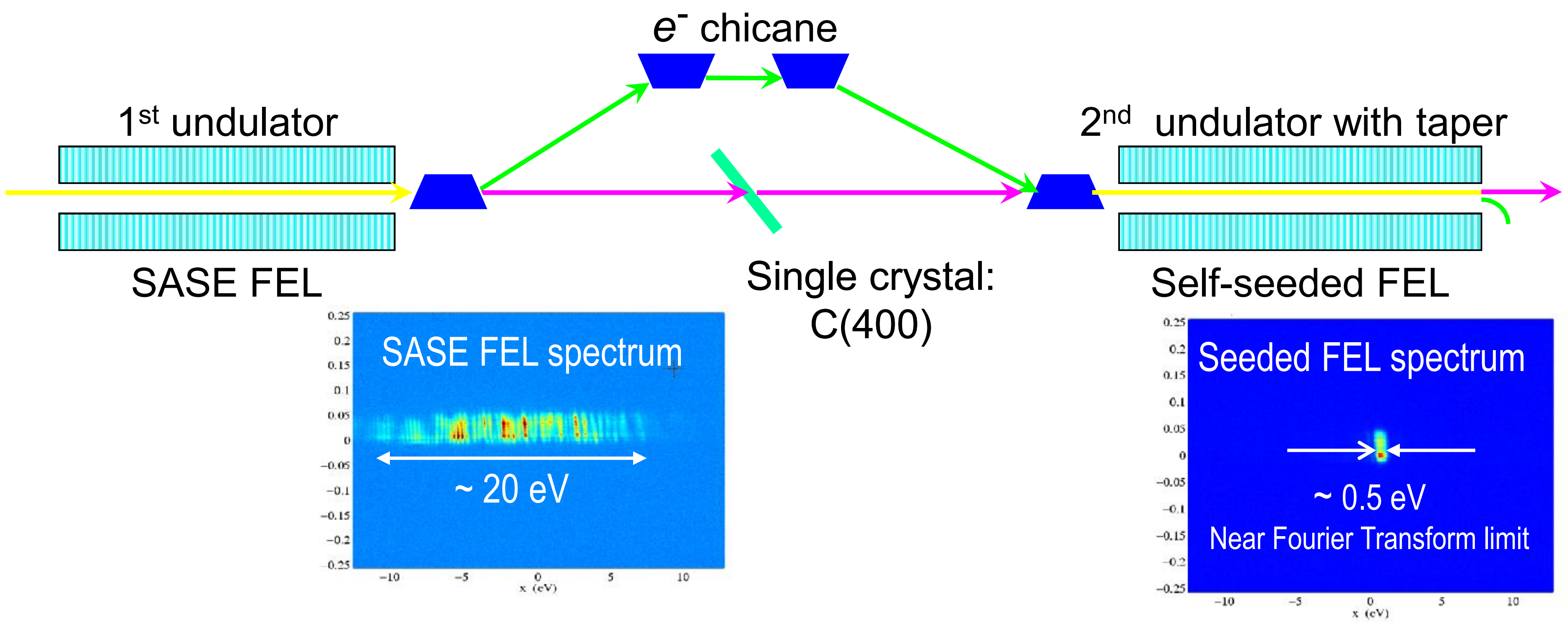
Induced current modulation in the electron beam



Harmonic content in the beam allows for radiation at a harmonic of the modulating wavelength

Self-seeded FELs

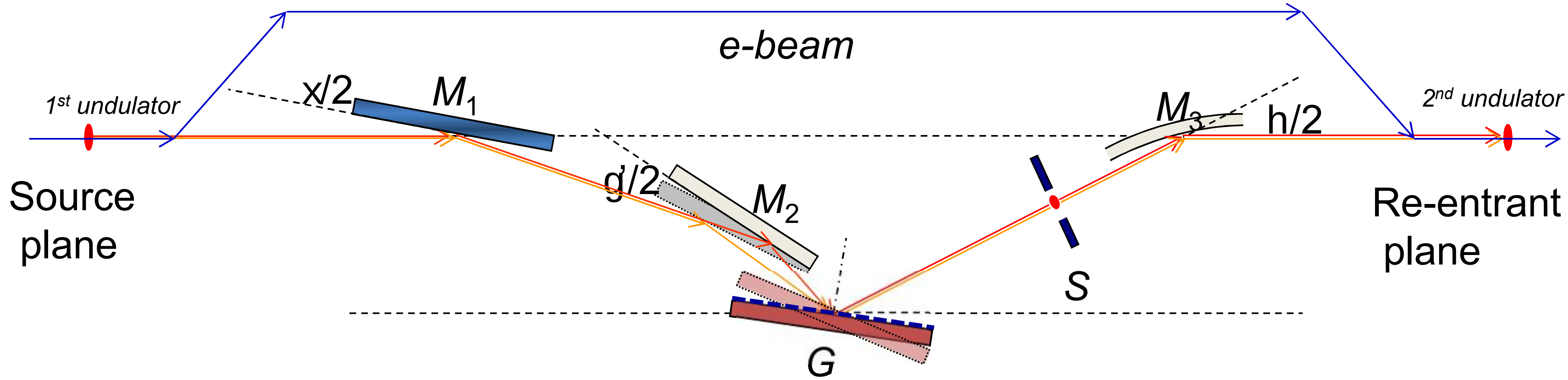
LCLS Hard X-ray Self Seeding – demonstrated at 1.5 Å



Initial results: 40x reduction in BW (40x increase in peak brightness)

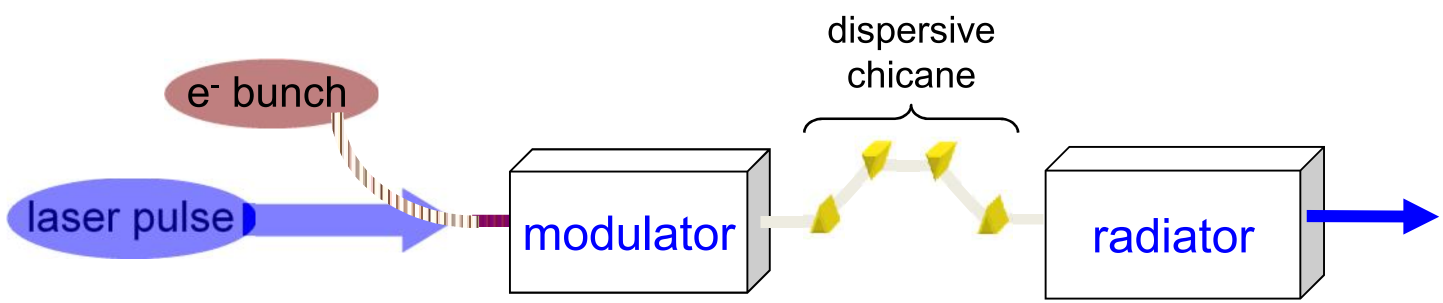
Self-seeded FELs

LCLS Soft X-ray Self Seeding – in planning stages



Phil Heimann, SLAC

High-gain harmonic generation (HGHG)



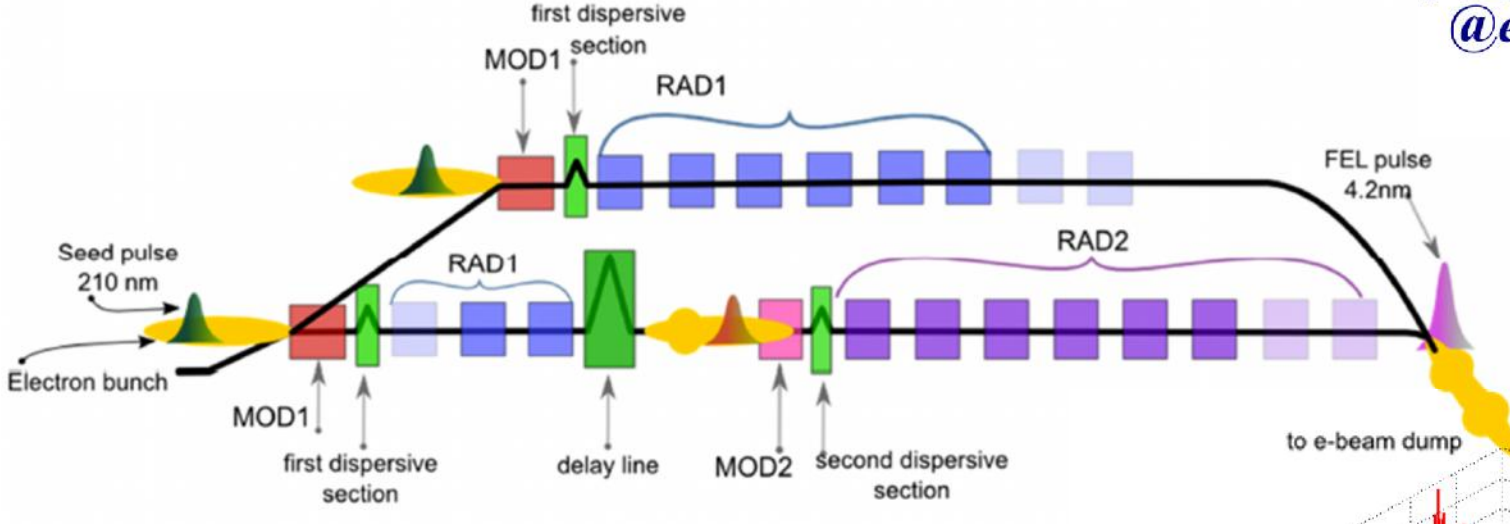
$$\lambda_{laser} = \lambda_{x-ray}^{modulator} = \frac{\lambda_{undulator}^{modulator}}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

$$\lambda_{x-ray}^{radiator} = \frac{\lambda_{x-ray}^{modulator}}{n} = \frac{\lambda_{undulator}^{radiator}}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

n ~ a few to ~10

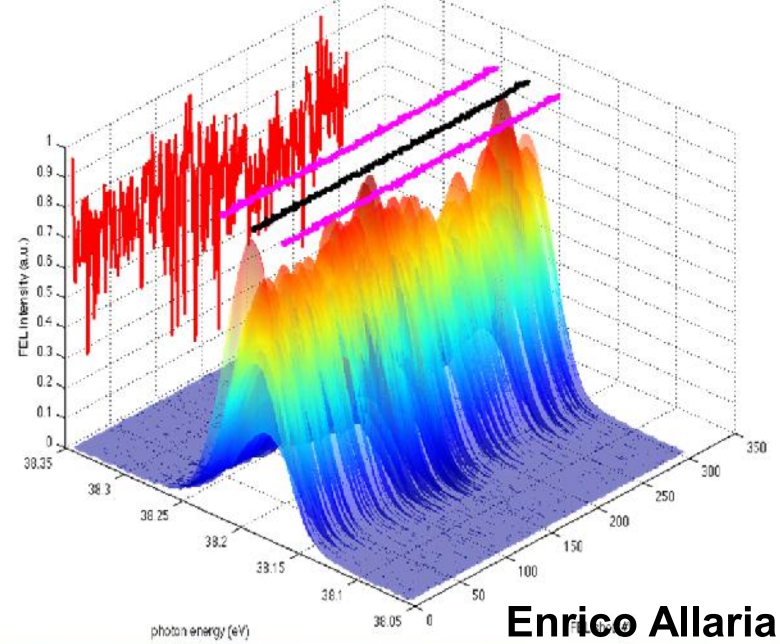
L.-H. Yu et al, Science 289 932-934 (2000)

FERMI@elettra demonstrates HGHG at ~10th harmonic (~20 nm)



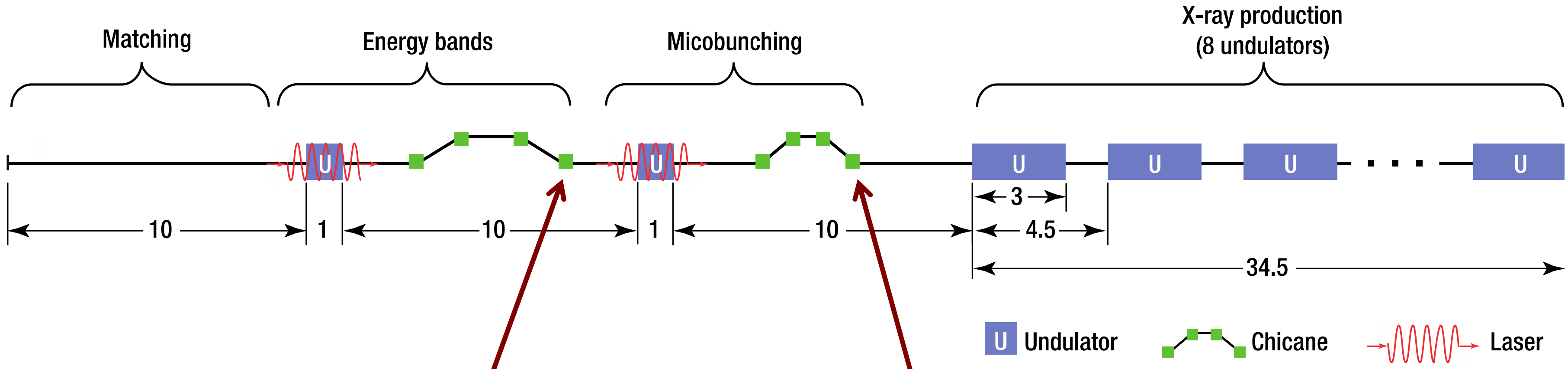
- UV laser seed (~200 nm)
- FEL gain at 20 nm
- 4 nm FEL cascade under construction

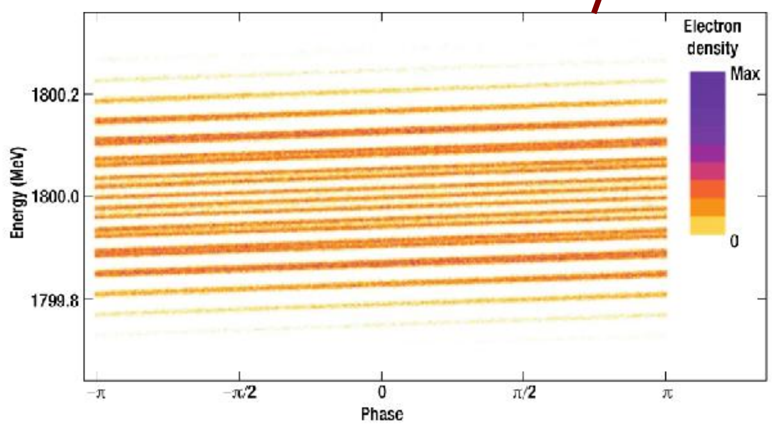
FEL photon energy ~ **38 eV**
Photon energy fluctuations = **1.1 meV (RMS)**
FEL bandwidth = **5.9e^{-4} (RMS)**
FEL bandwidth fluctuations = **3% (RMS)**

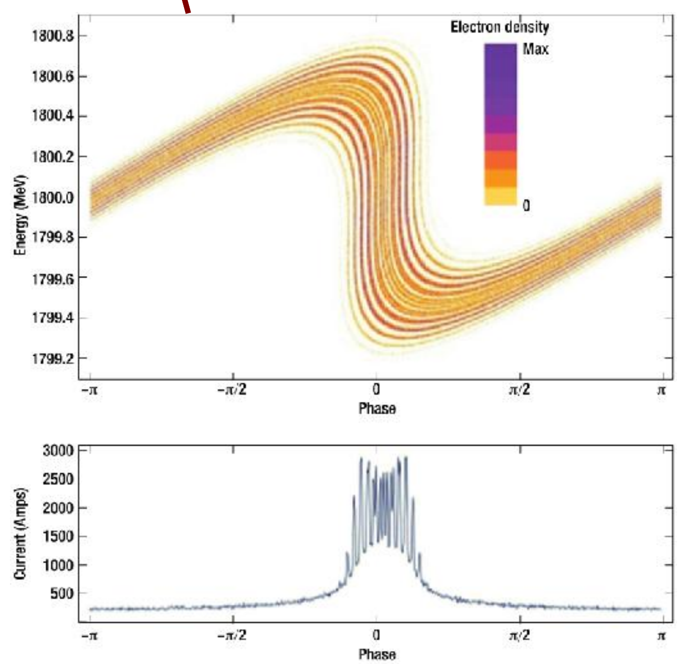


Enrico Allaria

Laser seeded FELs – ECHO







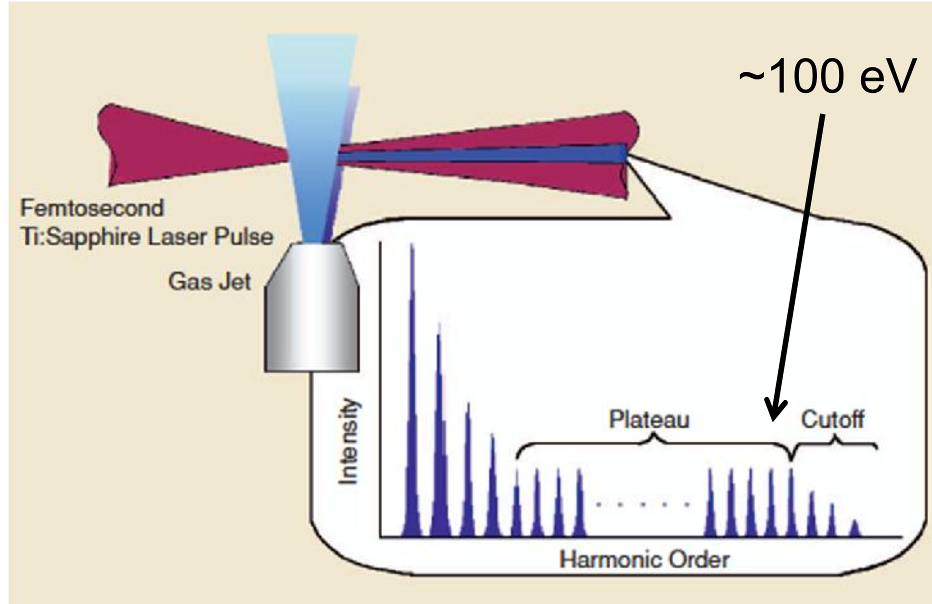
- **Developing R&D plans**
  - **Beam experiments**
  - **Laser developments**

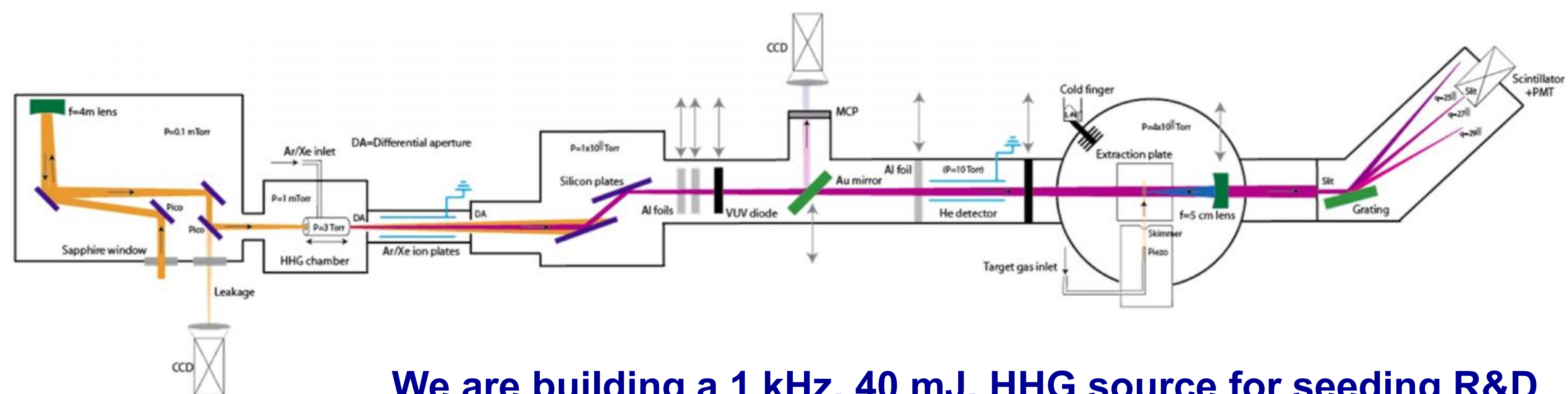
EEHG
HHG
HGHG

Stupakov, G., *Using the Beam-Echo Effect for Generation of Short-Wavelength Radiation,* Physical Review Letters **102** (2009) 074801

HHG seeded FEL R&D

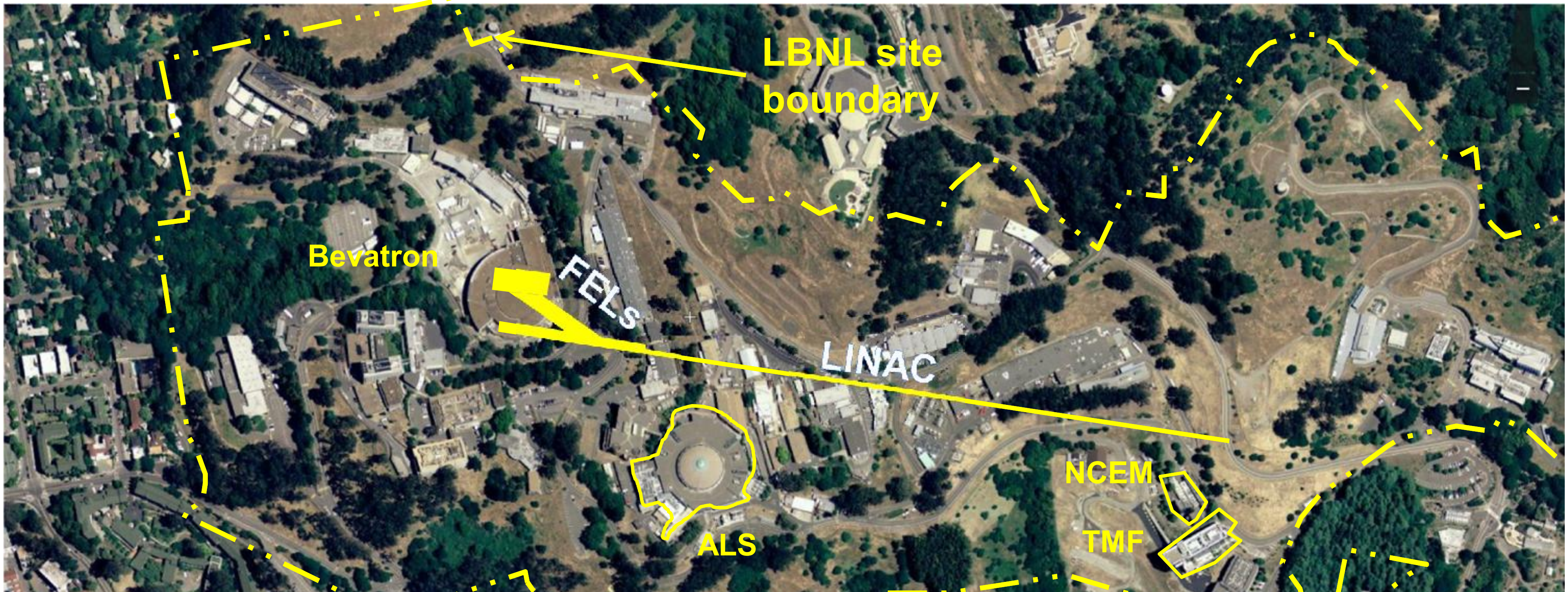
- **HHG seeding at 50 – 100 eV**
- **HHG seeding demonstrated at 61.5 nm (SCSS)**
- **Harmonic generation in FEL to reach 1 nm**

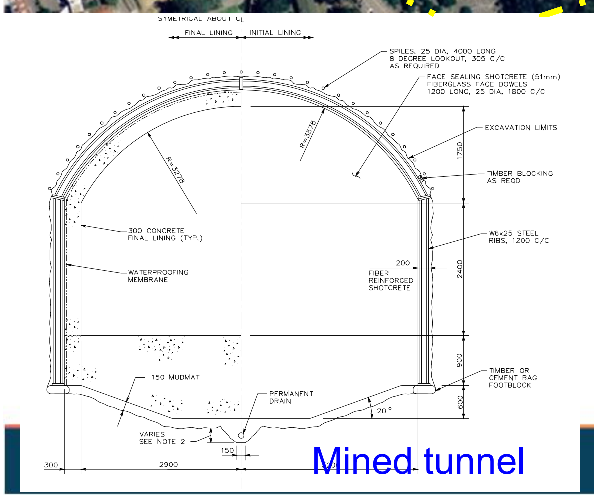


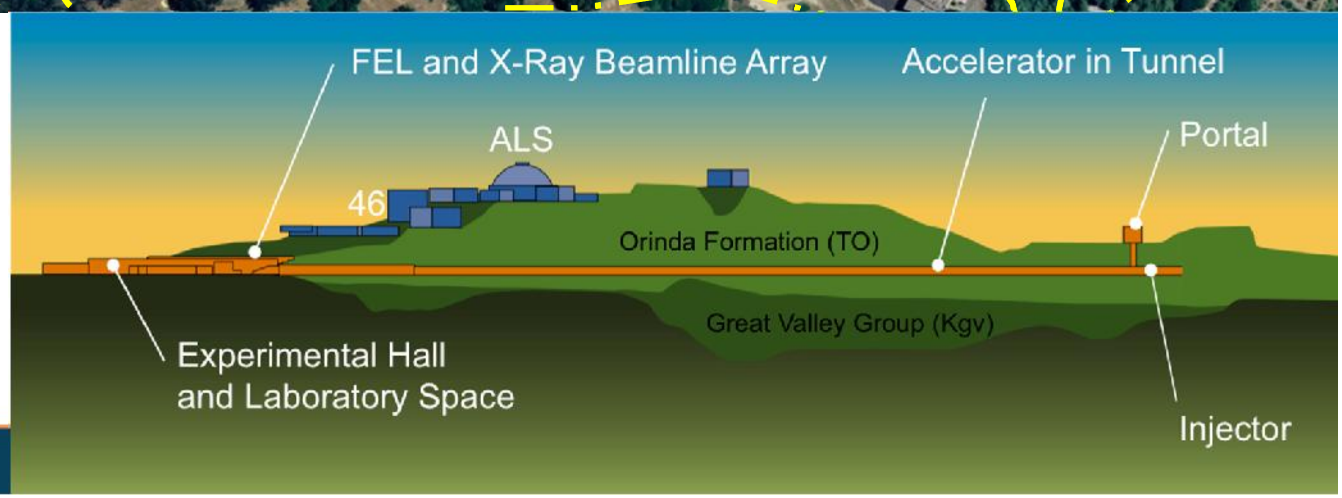


We are building a 1 kHz, 40 mJ, HHG source for seeding R&D

NGLS at the LBNL site



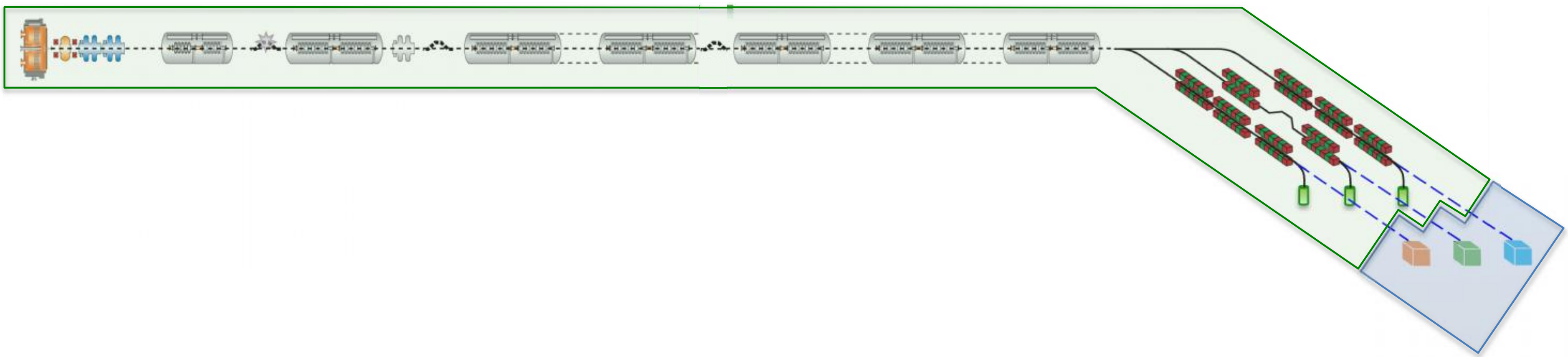




Summary

- DOE has approved Mission Need for a Next Generation Light Source
  - LBNL led the effort
    - We are:
      - Developing science case and experimental requirements
      - Optimizing machine design to best meet science needs
      - Executing and developing R&D plans
      - Strengthening and building collaborations
        - Seeking partnership with FNAL
          - Expertise in SCRF and cryosystems

NGLS DESIGN STUDY AND ACCELERATOR R&D TEAM

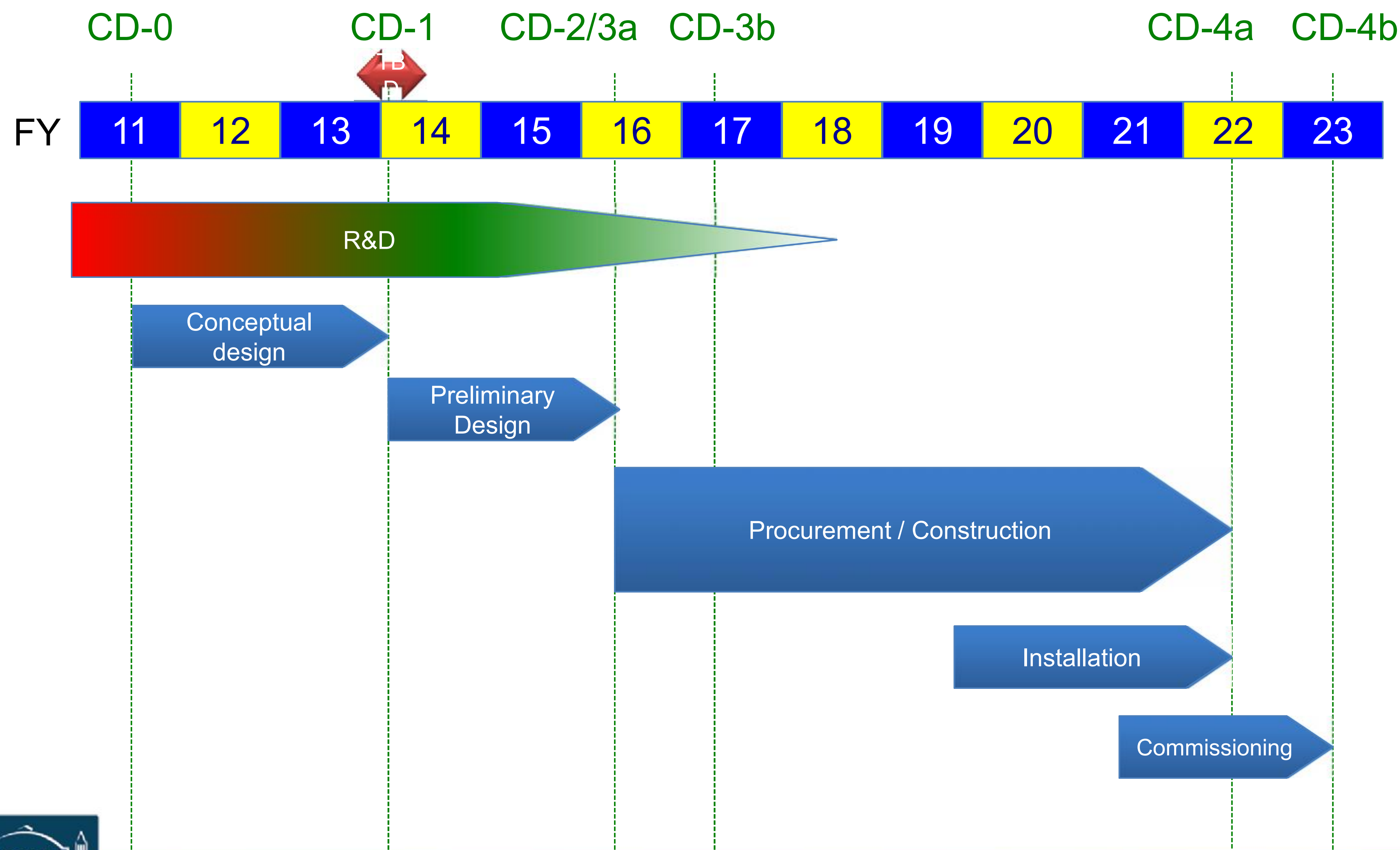


B. Austin, K.M. Baptiste, D. Bowring, J.M. Byrd, J.N. Corlett, P. Denes, S. DeSantis, R. Donahue, L. Doolittle, P. Emma, D. Filippetto, J. Floyd, J. Harkins, G. Huang, T. Koettig, S. Kwiatkowski, D. Li, H. Nishimura, T.P. Lou, H.A. Padmore, C. Papadopoulos, C. Pappas, G. Penn, M. Placidi, S. Prestemon, D. Prosnitz, J. Qiang, A. Ratti, M. Reinsch, D.S. Robin, F. Sannibale, R. Schlueter, R.W. Schoenlein, A. Sessler, J.W. Staples, C. Steier, C. Sun, T. Vecchione, M. Venturini, W. Wan, R. Wells, R. Wilcox, J. Wurtele

Backup slides

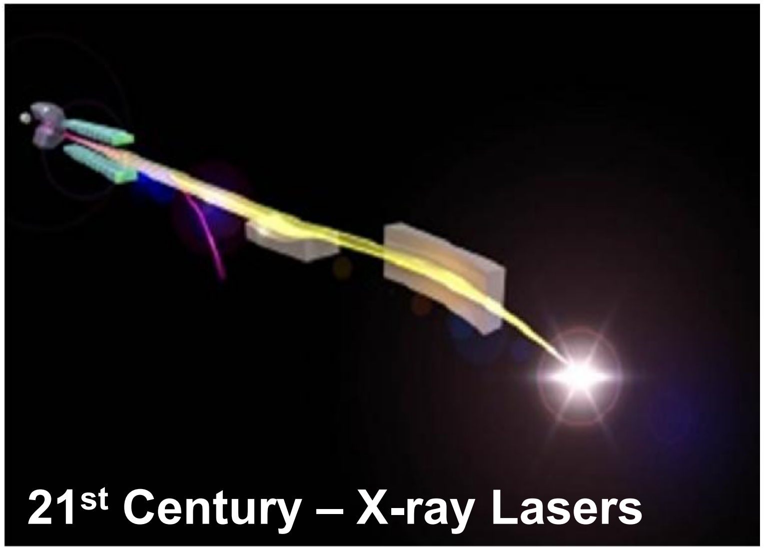
NGLS next generation light source

Summary schedule
(for planning purposes)



New era in X-ray Science: Nobel Prizes for X-rays and lasers portend the future scientific impact of true X-ray lasers

NGLS
next generation light source



Nobel Prizes – Laser Related

1964: Townes, Basov, Prokhorov
1971: Gabor
1981: Bloembergen, Schawlow
1997: Cohen-Tannoudji, Chu, Phillips
1999: Zewail
2000: Alferov, Kroemer
2001: Cornell, Ketterle, Wieman
2005: Hansch, Hall

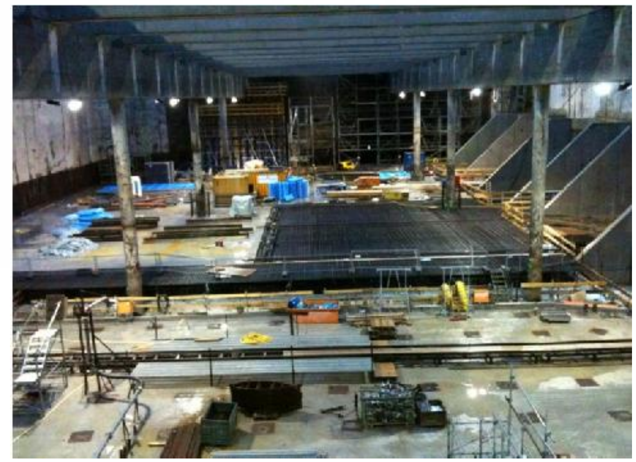
Nobel Prizes – X-ray Related

1901: Röntgen
1914: von Laue
1915: Bragg, Bragg
1917: Barkla
1924: Siegbahn
1927: Compton
1936: Debye
1962: Perutz, Kendrew
1962: Crick, Watson, Wilkins
1964: Hodgkin
1976: Lipscomb
1979: Cormack, Hounsfield
1981: Siegbahn
1985: Hauptman, Karle
1988: Deisenhofer, Huber, Michel
1997: Boyer, Walker
2006: Kornberg
2009: Ramakrishnan, Steitz, Yonath

X-ray lasers and X-ray science are developing rapidly

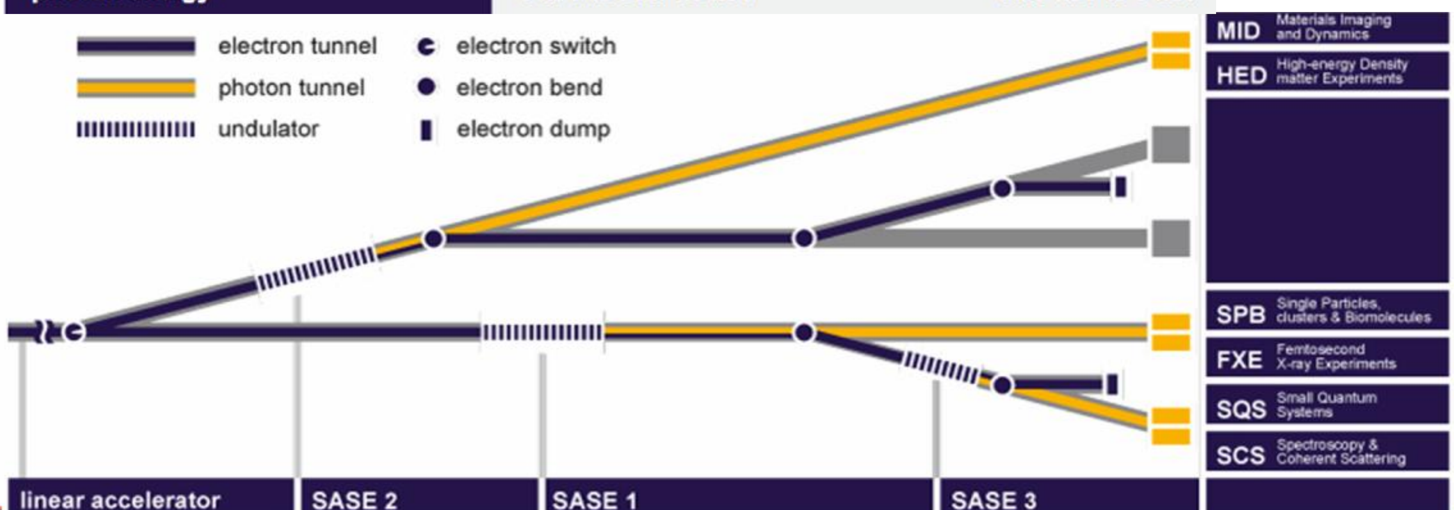
NGLS next generation light source

- Superconducting linac
- 30 kHz (burst mode)
- Soft and hard X-rays
- Operational in 2015



Experimental Hall

	SASE 1 + 2	SASE 3
wavelengths	0.4 nm to below 0.05 nm	4.7 nm to 0.4 nm
photon energy	3 keV to over 25 keV	0.26 keV to 3 keV



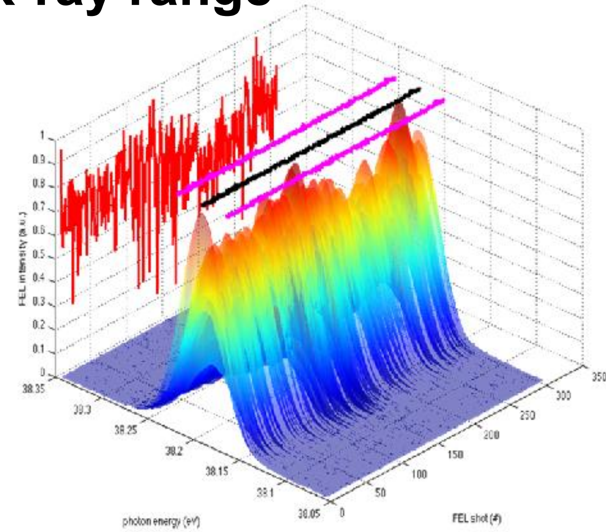
X-ray lasers and X-ray science are developing rapidly

World's first seeded X-ray FEL – tunable in soft x-ray range

FERMI @elettra

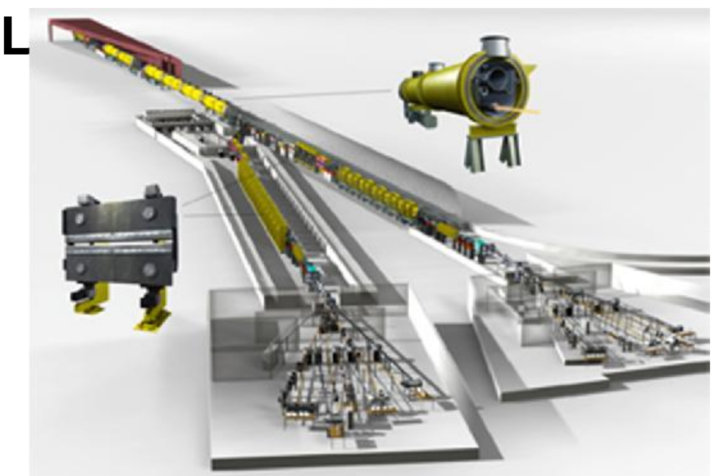
- UV laser seed (200 nm)
- FEL gain at 20 nm
- 1 nm FEL under construction

FEL photon energy ~ 38 eV
Photon energy fluctuations = 1.1 meV (RMS)
FEL bandwidth = $5.9e^{-4}$ (RMS)
FEL bandwidth fluctuations = 3% (RMS)



ITALY

Upgrade of FLASH – World's first X-ray FEL



DESY

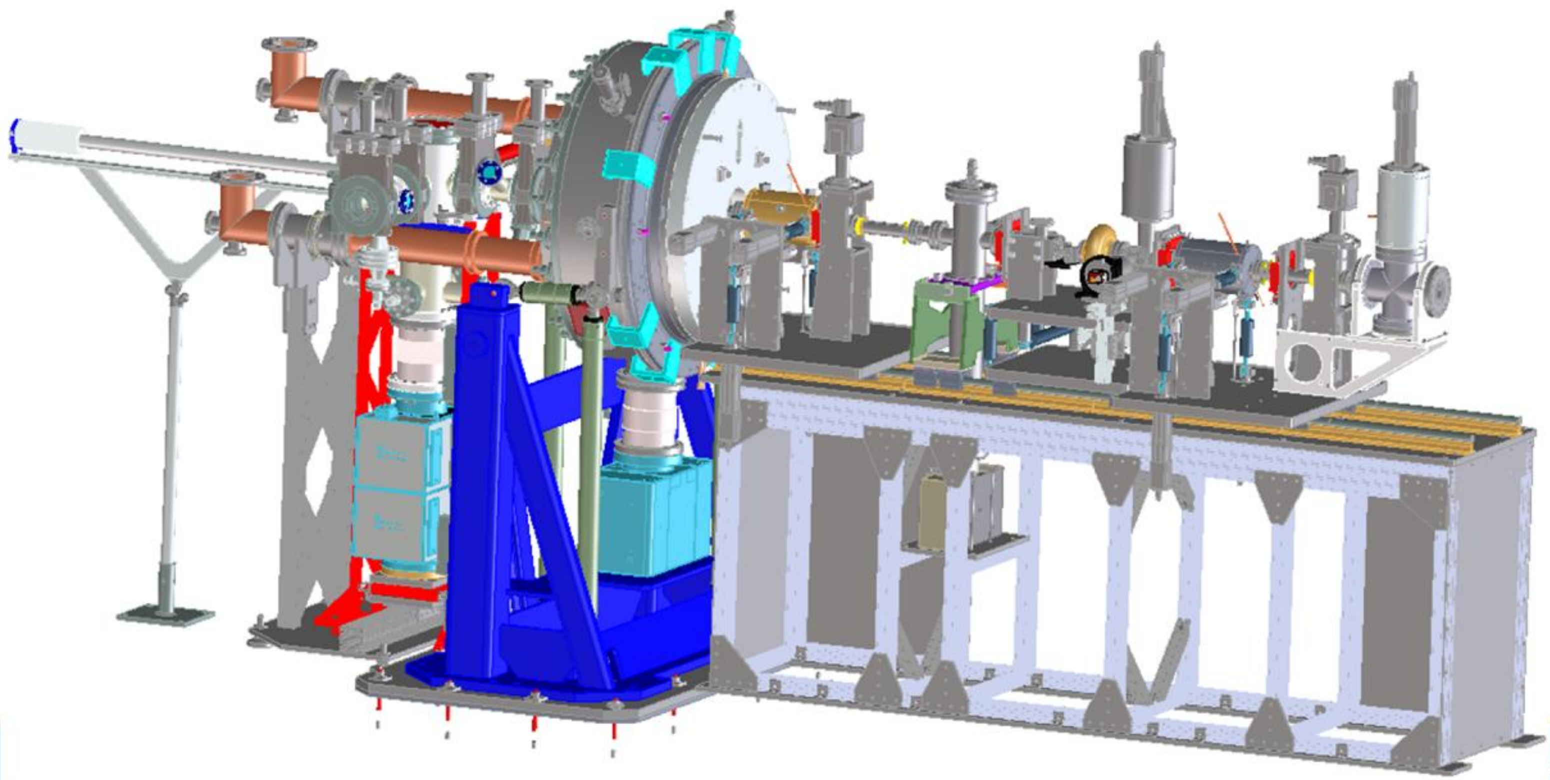
Superconducting
- Potential for CW operation)

FLASH-II
- Tunable (adjustable undulators)
- Seeded (coherent)

GERMANY

APEX Phase 0

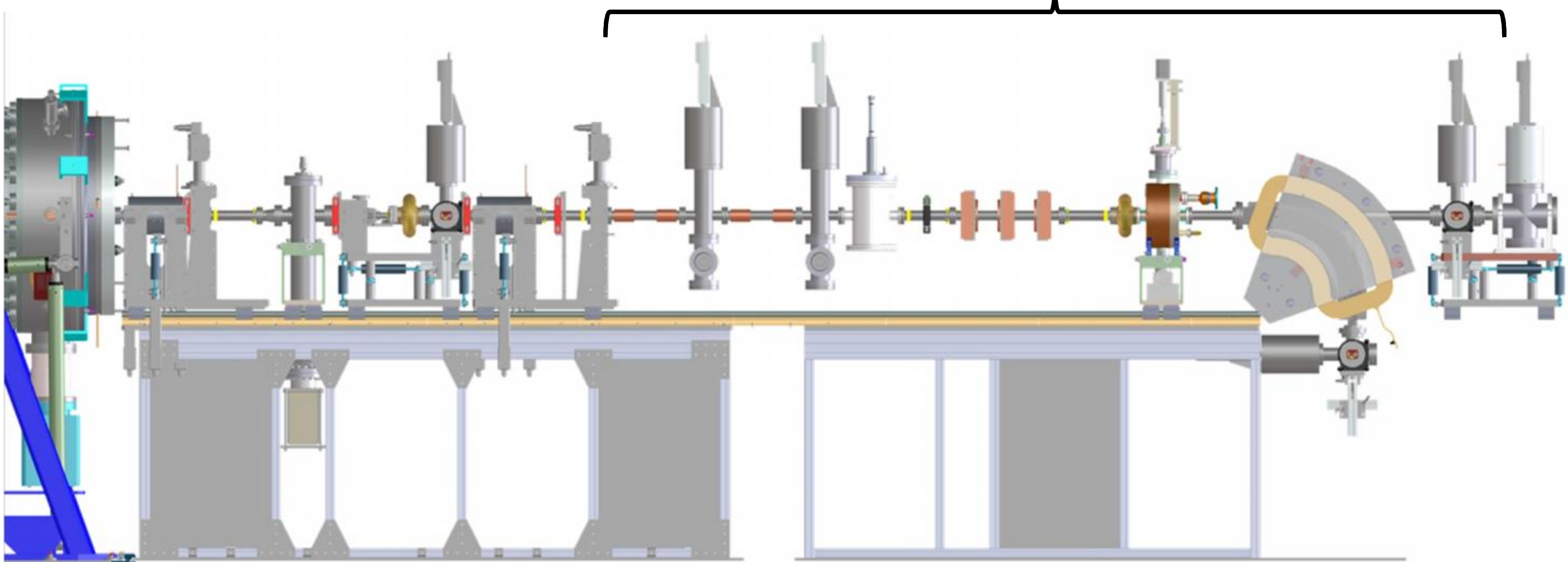
- Demonstration of gun RF performance
- Demonstration of vacuum performance with RF power
- Dark current characterization
- Cathode physics (lifetime, QE, intrinsic emittance) at full repetition rate



APEX Phase I adds diagnostics

- **Beam dynamics (6-D measurements)**
- **Diagnostics tests**
- **Low energy beam characterization**
- **Planned for spring 2012**

- Quadrupole triplet
- X-Y corrector
- Retractable slits
- Deflecting cavity
- YAG screens
- Spectrometer

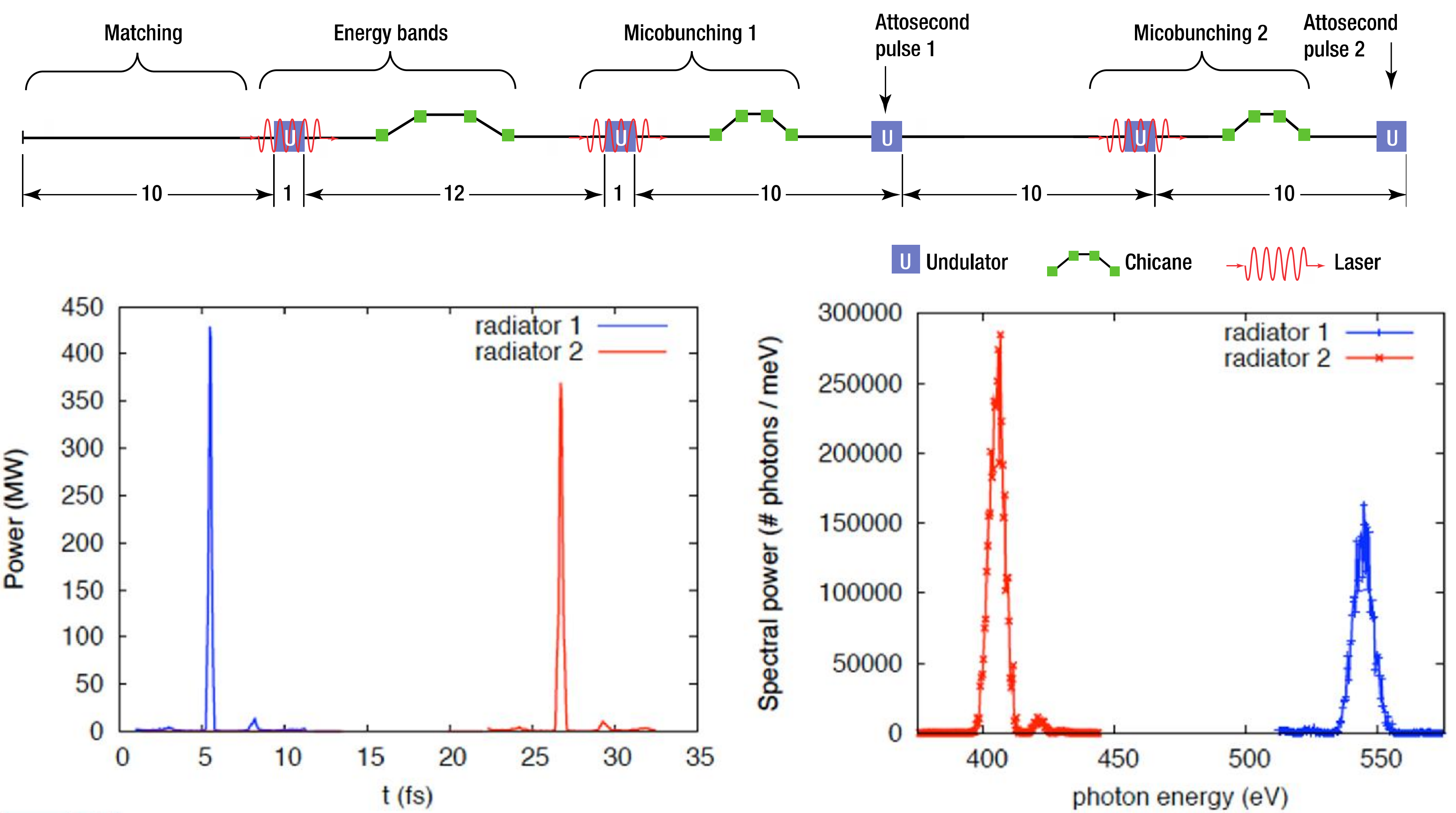


Diagnostics systems in collaboration with Cornell CLASSE

Technical developments since CD-0

- Increased tuning range (1.0 – 4.6 nm)
- Increased beam current (600 A)
- Larger energy spread (100 keV)
- Larger vacuum aperture in undulators (6 mm)
- Longer period undulators (29.4 mm)
- Increased minimum undulator K (1)
- Out-of-vacuum undulators
- Increased average β-function in FEL (15 m)
- Higher beam energy (2.4 GeV)
- Second bunch compressor
- Redesign of spreader including electrostatic septum

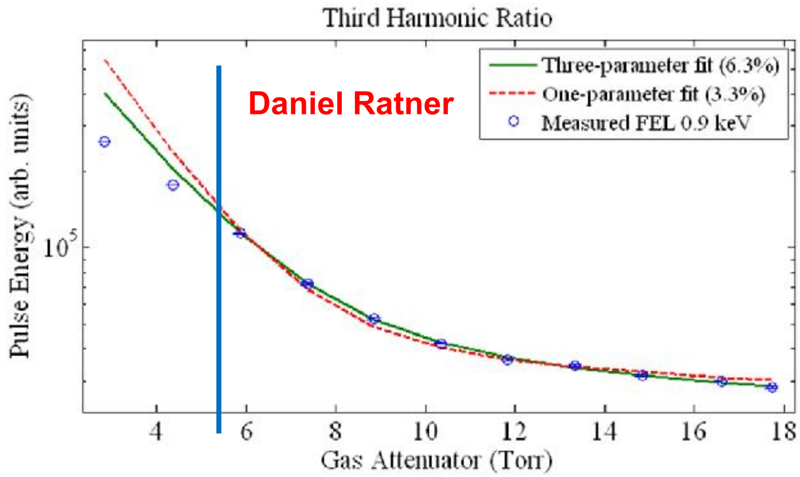
ECHO seeded 2-color attosecond



A. Zholents, G. Penn, "Obtaining two attosecond pulses for X-ray stimulated Raman spectroscopy", NIM–A, **612**, 2, (January 2010)

FEL harmonics measurements at LCLS

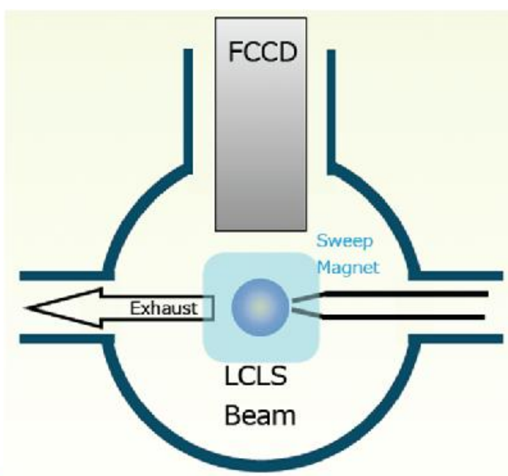
- **Now using filters**

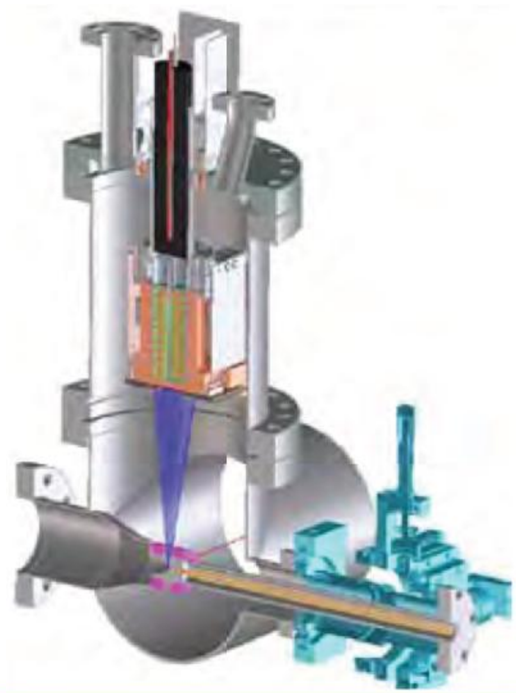


- **Fit to detected signal level with attenuators**

$$I \text{ » } I_0 \left(f_1 e^{-l_1 P_1} + f_3 e^{-l_3 P_3} + f_5 e^{-l_5 P_5} + \ldots \right)$$

- **Future using spectroscopic fast CCD detector**
  - **LBNL detector**





Instrumentation and diagnostics R&D

- **Motivation**
  - Diagnostics to optimize performance, control and feedback systems to stabilize beam

- High–resolution for high–brightness beams
- Large dynamic range for flexible operating modes
- Non-intercepting for high beam power
- High repetition rate
- X-ray beam and electron beam systems
  - Beam position monitors
  - Transverse profile monitors
  - Longitudinal profile monitors
  - Beam energy measurements
  - Beam arrival time monitors
  - Current monitors using toroids
  - Beam loss monitors

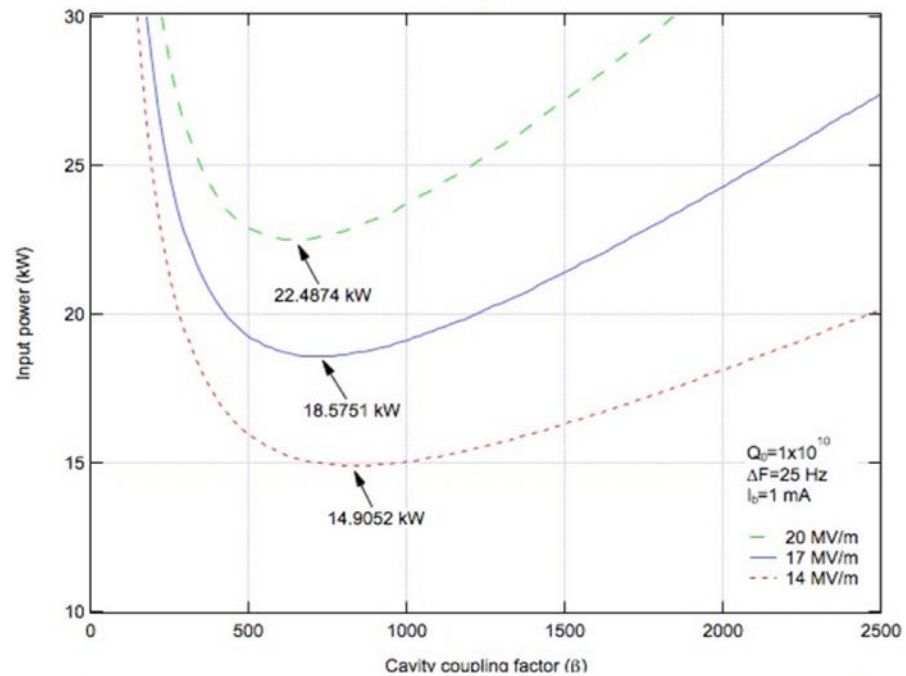
SCRF linac power requirements (CD-0)

NGLS next generation light source

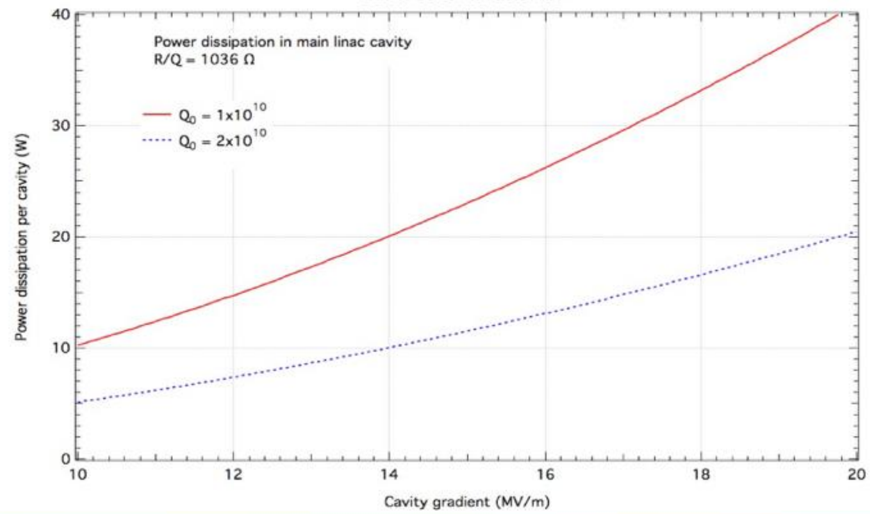
$$P_{Input} = \frac{P_{Cavity}}{4\beta}\left[\left(1+\beta+\frac{P_{Beam}}{P_{Cavity}}\right)^2 + \left(2Q_o\frac{\Delta f}{F_{RF}}\right)^2\right]$$

$$P_{Cavity} = \frac{V^2_{Cavity}}{Q_0 \frac{R}{Q}} \qquad P_{Beam} = I_{Beam} V_{Cavity} \cos(y_{Beam})$$

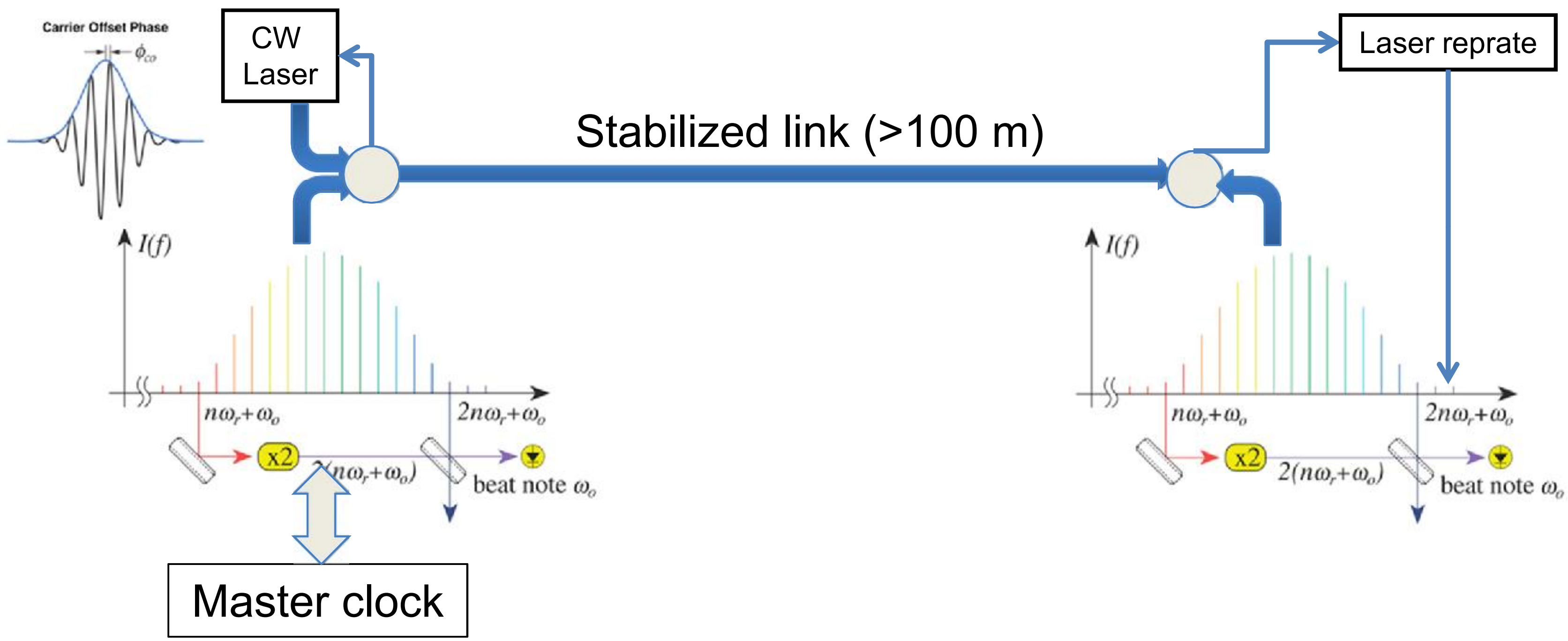
RF frequency 1.3 GHz
Cavity tuning excursion ±25 Hz
y_{Beam}<15°
R/Q 1036 Ω
Cavity length 1.038 m
Q_o 1×10^{10}
I_{beam} 1 mA



- RF power requirement is ~20 kW per cavity
  - 7 cavities per cryomodule ≈ 140 kW per linac cryomodule
  - 27 cryomodules
  - **3.8 MW** RF power capacity
  - Dominated by beam power requirement

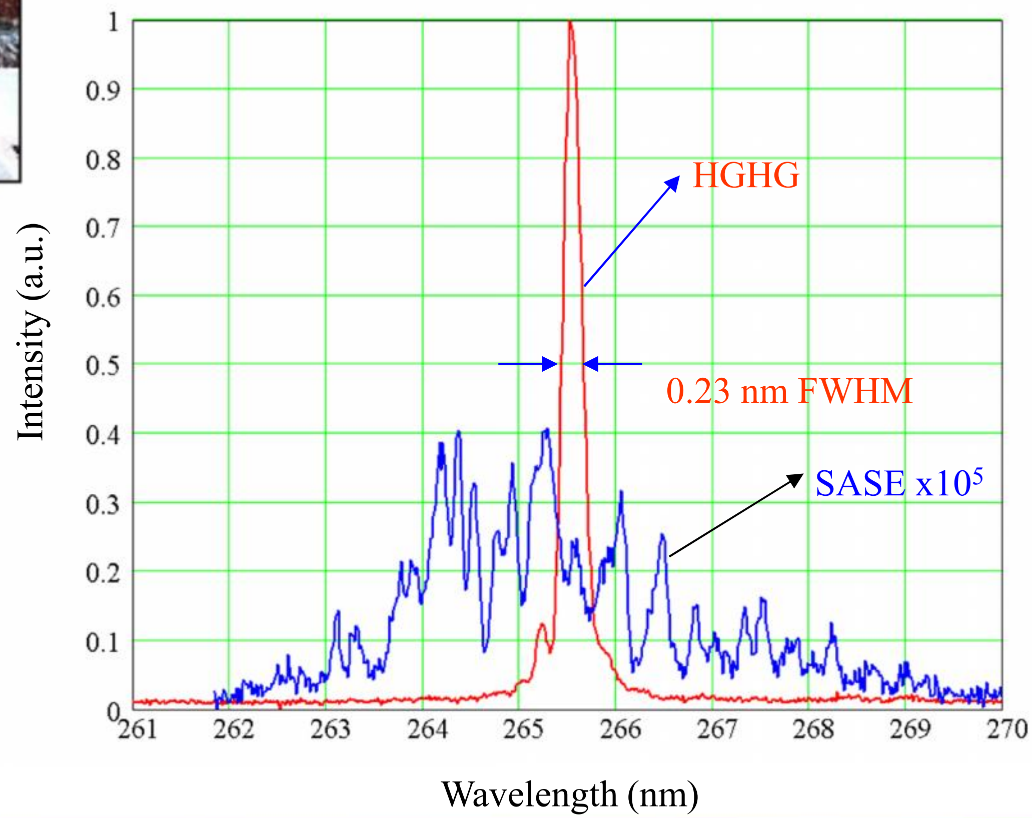


Timing & synchronization R&D



HGHG demonstrated at Brookhaven SDL

- Spectrum of HGHG and unsaturated SASE at 266 nm under the same electron beam condition
  - Note SASE at saturation would still be order of magnitude lower intensity



L.-H. Yu et al, Phys. Rev. Let. Vol 91, No. 7, (2003)